NATIONAL RESEARCH COUNCIL

AMERICAN GEOPHYSICAL UNION
TRANSACTIONS OF 1940

PARTS III-B AND III-C

REGIONAL MEETING
SEATTLE, WASHINGTON, JUNE, 1940

REPORTS AND PAPERS
(B) WESTERN INTERSTATE SNOW-SURVEY CONFERENCE
AND (C) SECTION OF HYDROLOGY
(NORTH PACIFIC COAST AND NORTH CONTINENTAL DIVIDE AREAS)

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
SEPTEMBER, 1940

PREFACE

The Meeting at Seattle represents the last stage in the inauguration of Regional Meetings in the Western States.

The South Pacific Coast Area was the first to be organized by the Section of Hydrology of the American Geophysical Union, under the presidency of Dr. O. E. Meinzer, and has held meetings at Berkeley, Pasadena, Davis, Los Angeles, and Stanford University. A session is planned for January, 1941, at Sacramento.

The organization of the other Areas was perfected under the presidency of LeRoy K. Sherman. The South Continental Divide Area has held a Meeting at Denver and the North Continental Divide Area has held two meetings at Spokane. The Meeting at Seattle was held jointly by the North Pacific Coast and the North Continental Divide Areas.

The Western Interstate Snow-Survey Conference, organized at Reno in 1933, has shared in all of the Regional Meetings of the Section of Hydrology.

It is planned, under the leadership of the United States Weather Bureau, to hold an Eastern States Precipitation and Snow-Survey Conference September 16, 1940. An earlier Conference was held at Boston October 8, 1937, by the United States Weather Bureau and the United States Geological Survey in connection with the Meeting of the American Society of Civil Engineers.

Universities and scientific organizations have provided facilities and affiliation where joint meetings were possible. These included the University of Nevada, the University of California at Berkeley, the California Institute of Technology, the University of California at Davis and at Los Angeles, Stanford University, and the University of Washington. The American Association for the Advancement of Science (both Pacific Coast and National) and the Northwest Scientific Society have provided close affiliation at the Berkeley, Denver, Spokane, and Seattle Meetings.

The officers in charge of the Seattle Meeting were as follows:

American Geophysical Union

R. M. Field, President
W. C. Lowdermilk, Vice-President
J. A. Fleming, General Secretary

Section of Hydrology, American Geophysical Union

N. C. Grover, President
M. P. O'Brien, Vice-President
K. H. Beij, Secretary

North Continental Divide Area Regional Committee

O. W. Monson, Chairman
A. H. Tuttle
William A. Rockie
G. A. Hathaway
W. E. Maughan
C. S. Heidel
James C. Marr
H. T. Gisborne
D. B. Freeman

North Pacific Regional Area Committee

J. C. Stevens, Chairman
George G. West, Secretary
Fred Merryfield
C. E. Webb
G. H. Canfield
Elmer Fisher
J. H. Ryan
R. A. Work
Joseph Jacobs
Norbert Leupold
R. G. Tyler

Program Committee, Regional Meeting, Section of Hydrology

J. C. Stevens, Chairman
O. W. Monson
George G. West, Secretary

Executive Committee, Western Interstate Snow-Survey Conference

H. P. Boardman, Chairman
J. C. Alter
George D. Clyde
Lynn Crandall
E. B. Debler
R. C. Farrow
H. T. Gisborne
O. H. Hoover
James E. Jones
Joseph Kittredge, Jr.
James C. Marr
O. W. Monson
F. H. Paget
R. L. Parshall
R. A. Work

Program Committee, Regional Meeting, Western Interstate Snow-Survey Conference

R. A. Work, Chairman
R. C. Farrow
Phil E. Church

Twenty-two papers and reports were presented at three sessions of the Western Interstate Snow-Survey Conference. These were arranged under the following general subjects: (1) Forecasting, R. A. Work, Chairman; (2) equipment, R. C. Farrow, Chairman; (3) activities, O. W. Monson, Chairman.

These sessions were followed by a joint session of the Snow-Survey Conference, the Section of Hydrology of the American Geophysical Union, and the American Meteorological Society on the general topic of floods and under the chairmanship of Phil E. Church, Merrill Bernard, and J. Cecil Alter. Seven papers were presented.

Two sessions were held by the Section of Hydrology of the American Geophysical Union under the chairmanship of J. C. Stevens and O. W. Monson, respectively, and at which seven papers and reports were read.

At joint luncheons, in which the American Meteorological Society also participated, motion-films were presented as follows: "Snow-surveying in the Cascades" by R. A. Work (June 19); "Formation of snow-crystals on the mountains and in the laboratory in Japan," a sound-film prepared by Ukitiro Nakaya of the Hokkaido University (June 20); "Story of electric service from the snow-fields to the home" by the Washington Water Power Company (June 21).

At the joint dinner (June 20), in which the American Meteorological Society also participated, the motion-film in color "Snow-surveying in the Central Sierra" was exhibited by Walter Herz. Following the film, nine speakers discussed the subject "Accuracy of forecasts in the Pacific Northwest in 1938-39."

Interesting features of the Meeting were (1) the exhibit of instruments used in collecting hydrologic data and (2) the extended discussions of the papers and reports.

The manuscripts were assembled and edited by Messrs. West, J. E. Church, and Elges. Final editing and preparation of illustrations for publication were done by General Secretary J. A. Fleming of the Union. We are indebted to Messrs. W. E. Scott and J. J. Capello for typing of master-copy, to W. C. Hendrix for redrawing of numerous illustrations, and to J. W. Green and W. F. Steiner for necessary photographic work. As for past Transactions, grateful appreciation for excellence of planographic publication is made to the Kirby Lithographic Company, Inc., of Washington, D. C. The cost of publication was shared by the American Geophysical Union and members and organizations interested in the Snow-Survey Conference.

J. A. Fleming, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

JOINT REGIONAL MEETING

NORTH PACIFIC COAST AND NORTH CONTINENTAL DIVIDE AREAS

WESTERN INTERSTATE SNOW-SURVEY CONFERENCE,
SECTION E AMERICAN ASSOCIATION FOR THE
ADVANCEMENT OF SCIENCE, AND
SECTION OF HYDROLOGY

June 19-22, 1940

PART III-B

WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

REPORTS AND PAPERS

Seattle, Washington
June 19-20, 1940

CONTENTS

JOINT REGIONAL MEETING AT SEATTLE, WASHINGTON, JUNE 19-21, 1940

REPORTS AND PAPERS
WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

Morning session, June 19, 1940

Page

FORECASTING. R. A. WORK, Chairman. 835

A quantitative forecast-system for power- and flood-warning in the Androscoggin River Basin, Maine. PAUL L. BEAN and PHILIP W. THOMAS. 835

Discussion. PHILIP W. THOMAS, ERIC HINTON, and L. STANDISH HALL. 847

A quantitative forecast-system of runoff based on snow-surveys at the mean elevation of the snow-cover. JOHN V. SALO. (See also Difficulties of snow-surveying, p. 992). . . 858

Discussion. JOHN V. SALO and H. P. BOARDMAN. 870

Soil-moisture studies as an aid in forecasting runoff from snow-cover. GEORGE D. CLYDE . 871

Map of western snow-survey systems. J. E. CHURCH 874

Present trends in improving forecasting in the Humboldt Basin, Nevada. CARL ELGES. . . . 874

A proposed snow-survey system for the Yakima Basin. H. P. BOARDMAN 878

Discussion. LAWRENCE C. FISHER, JAMES C. MARR, and E. H. COLLINS 887

Report on snow-surveys of 1939 in the Chelan Basin. E. H. COLLINS. 887

Snow-surveying in the Cascades: A film. R. A. WORK. (Lunch session). 892

Afternoon session, June 19, 1940

The mountain snow-survey: Its Genesis, Exodus, and Revelation. J. CECIL ALTER 892

Discussion. J. E. CHURCH 899

EQUIPMENT. R. C. FARROW, Chairman. 901

A plan for the study of snow-cohesion and snow-loads in estimating the necessary strength of roofs against snow-overload. R. A. WORK 901

Discussion. J. E. CHURCH 901

Improvements to the Tucker motor-sled to surmount difficulties in traversing powder-snow. JOHN T. RYAN. 902

Discussion. E. M. TUCKER 904

Improvement of snow-survey equipment. PHILIP S. COWGILL. 904

Tests of Mount Rose snow-scale No. 101. J. C. STEVENS. 905

New spring-balances by John Chatillon and Sons. 908

Discussion. JOHN CHATILLON AND SONS, CARL ELGES, and J. E. CHURCH. 909

Problem of using calcium chloride in precipitation-gages. CARL ELGES 911

Calcium-chloride solutions in the operation of precipitation-gages. ASHTON R. CODD . . . 913

Discussion. MERRILL BERNARD and JOHN C. STEVENS. 915

EQUIPMENT--Concluded

Page

Snow-sampling equipment for granular and crusted snow in New England. PAUL WEBSTER BEAN and FREDERICK A. BENDTSEN 916

Discussion. J. E. CHURCH 919

Morning session, June 20, 1940

ACTIVITIES. O. W. MONSON, Chairman 920

Problems of the Division of Irrigation in forecasting water-supplies. W. W. McLAUGHLIN . 920

Snow-activities of the United States Park Service. R. D. WATERHOUSE. 920

Research on snow by the Forest Service. CHAS. A. CONNAUGHTON 920

Discussion. J. CECIL ALTER, J. E. CHURCH, and H. T. GISBORNE 925

Ski-etiquette and ski-safety. J. CARLISLE CROUCH 925

Ice-crusts and snow-settling at Snoqualmie Pass, season of 1939-40. PHIL E. CHURCH . . . 928

Discussion. J. E. CHURCH 932

Snow-types met in highway snow-removal. J. D. MacVICAR 932

JOINT MEETING OF WESTERN INTERSTATE SNOW-SURVEY CONFERENCE, SECTION OF HYDROLOGY OF THE AMERICAN GEOPHYSICAL UNION, AND AMERICAN METEOROLOGICAL SOCIETY

Formation of snow-crystals on the mountains and in the laboratory of Japan: A sound film. UKITIRO NAKAYA. (Lunch session). 935

Afternoon session, June 20, 1940

FLOODS. Chairmanship of PHIL E. CHURCH, MERRILL BERNARD, and J. CECIL ALTER. 935

Forecasting of stream-flow from melting snow. MERRILL BERNARD. 935

Some factors affecting frost-penetration. H. B. ATKINSON and CLYDE E. BAY. 935

Discussion. KENNETH L. ROBERTS, PAUL L. BEAN, EDWIN S. CULLINGS, ASHTON R. CODD, FRED D. McLAREN, and H. H. BURT. 949

The relation of snow to maximum flood-peaks. WALTER J. PARSONS, JR. 951

The relation of snow to maximum flood-peaks: A discussion. J. E. CHURCH 953

Discussion. R. H. ELLIOTT and L. STANDISH HALL 968

Unit-hydrograph. R. H. ELLIOTT and LEROY K. SHERMAN. 969

Ice in the northern streams of the United States, WALTER J. PARSONS, JR. 970

Discussion. J. E. CHURCH 973

Winter overflow from ice-gorging on shallow streams. J. C. STEVENS 973

Joint dinner session, June 20, 1940

Page
Color-film on snow-surveying in the Central Sierra. WALTER HERZ. 979

Discussion. J. BJERKNES. 979

Forecast accuracy of water-supply as made from snow-surveys. R. A. WORK, Chairman. 979

Standards and terminology. R. A. WORK. 979

Discussion. W. W. McLAUGHLIN, HAROLD CONKLING, JAMES C. MARR, O. W. MONSON, and CARL ELGES 980

Regional reports for the northern watersheds. 981

(1) Accuracy of Oregon water-supply forecasts, 1936-1939. R. A. WORK and J. H. RYAN. . . 981

(2) Accuracy of stream-forecasts on the Boise River, Idaho, 1939. JAMES C. MARR. 984

(3) Forecast and runoff, Lakes Coeur d'Alene and Chelan, 1939. WALTER E. JOHNSON 984

(4) Accuracy of stream-forecasts in Montana. O. W. MONSON. 986

(5) Upper Missouri River forecasts at Fort Peck, 1938 and 1939. D. B. FREEMAN. 986

(6) Accuracy of forecasts in British Columbia in 1939. R. C. FARROW. 987

(7) The accuracy of forecasts in the Pacific Northwest with reference only to the Bow and Saint Mary River basins. W. T. McFARLANE. 988

Addendum: Difficulties of snow-surveying. JOHN V. SALO. (See also p. 858) 992

Minutes of Seattle Meeting

Report, Chairmen of Executive Committee, Western Interstate Snow-Survey Conference. H. P. BOARDMAN. 1051

Personnel, Executive Committee, Western Interstate Snow-Survey Conference, 1940-42. 1052

Minutes of the Regional Meeting of the Section of Hydrology, American Geophysical Union, at Seattle, Washington, June 19-21, 1940. GEO. G. WEST, Secretary 1053

Resolution on the use of the median instead of the average. 1053

Appendix A--Record of 80 members and guests who attended the joint Regional Meetings of the Section of Hydrology, the Western Interstate Snow-Survey Conference, and the American Meteorological Society at Seattle, Washington, June 19-21, 1940. 1054

Index of names for Part III-B 1058

Index of subjects for Part III-B. 1058

FORECASTING

R. A. Work, Chairman

A QUANTITATIVE FORECAST-SYSTEM FOR POWER- AND FLOOD-WARNING IN THE ANDROSCOGGIN RIVER BASIN, MAINE

Paul L. Bean and Philip W. Thomas

(Presented by J. E. Church)

[Great pleasure is taken in presenting the following two papers not only because they introduce our eastern colleagues and broaden our outlook but especially because they introduce the problem of winter melting and the development of quantitative snow-surveying to offset it. The success of these pioneers is both unexpected and gratifying. The heavy precipitation in the form of rain at lower altitudes this season will afford a supreme test to the percentage-system so far found sufficient to meet the requirements of vast areas and high altitudes in the west.--(J. E. Church)]

Snow-surveys

Snow-surveying in the Androscoggin River Basin as now conducted is the result of an increase in the demand for water for power-purposes and a steady increase in the value of the water yielded by the drainage-area for manufacturing purposes.

In the early years from 1881 to 1900, the developments for power usually utilized the flow of the River available for about 60 per cent of the average year and such river-regulation as then existed was conducted in a more or less haphazard manner. The increase in power-development along the River, and especially during the excessively dry period from 1900 to 1906, when the summer flows dropped to 0.1 of a cubic foot per second per square mile, convinced the power-users that something must be done to develop the storage-resources of the Basin, increase the low-water flows, and utilize such resources intelligently.

At that time a storage-capacity of 20 billion cubic feet had been developed and was in operation. Such capacity, however, was entirely inadequate to maintain satisfactory low-water flows as then operated. All agreed that further storage-developments were necessary.

In 1909 the four major industrial companies operating on the River met, and voluntarily organized to increase the storage-capacity available and in 1912 constructed the Aziscohos Reservoir with a capacity of 9.5 billion cubic feet, making a total storage-reserve of 29.5 billion cubic feet which has been available since.

The companies agreed to, and did require, that the flow at Berlin, New Hampshire, should not be permitted to fall below 1,550 cubic feet per second, or about 1.13 cfs per square mile, and set up an organization to accomplish this result.

The improvement in minimum flow was the difference between 0.1 cfs per square mile and 1.13 cfs per square mile at Berlin, New Hampshire. Incidentally, this is the first case, so far as our knowledge goes, whereby the cost of regulating the river-flow of an inter-State river has been assumed voluntarily by private companies and which has been in successful operation for 28 years. The cost of regulation to the contributing companies varies from about $0.25 per horsepower per year, to $1.25 per horsepower per year, depending largely on costs of maintenance. Nearly 60 per cent of this cost arises from taxes. The storage-system is operated without profit.

By 1912 those in charge of the river-regulation realized that the time had arrived when there was a distinct need of eliminating "guesses" from our calculations and snow-surveying in a modest way was started in the storage-area to increase the efficiency of river-regulation. It was not until many years later that the value of these surveys in predicting spring floods was manifest and, in 1936, the companies who pay the cost of these surveys admitted their value.

Description of the Androscoggin River Basin where these snow-surveys are made

The Androscoggin River Drainage-Basin totals 3,430 square miles, with eastern and western limits of the drainage-area at longitude 70° and 71° 15', respectively, while the northerly and

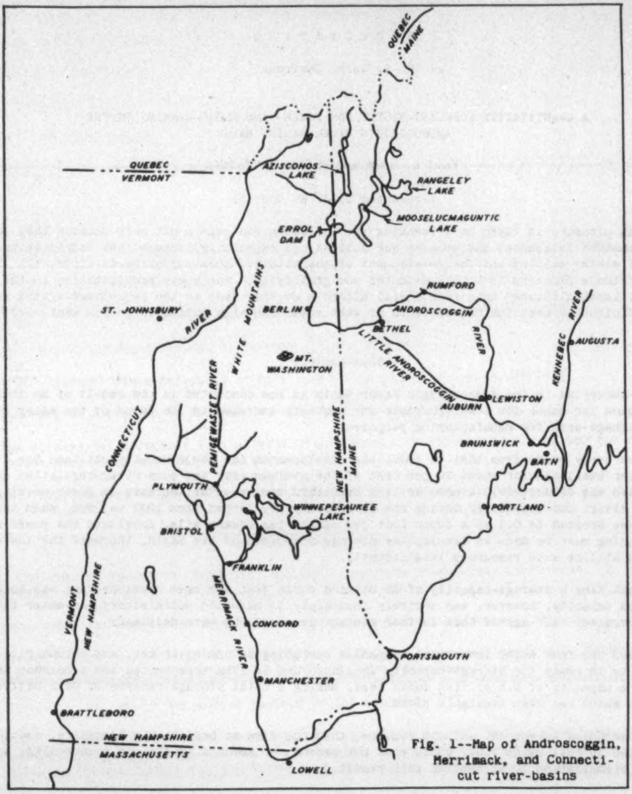

QUEBEC
MAINE
QUEBEC
VERMONT
AZISCOHOS LAKE
RANGELEY LAKE
MOOSELUCMAGUNTIC LAKE
ERROL DAM
RUMFORD
ST. JOHNSBURY
RIVER
WHITE MOUNTAINS
BERLIN
ANDROSCOGGIN
BETHEL
LITTLE ANDROSCOGGIN RIVER
RIVER
KENNEBEC RIVER
AUGUSTA
MT. WASHINGTON
PEMIGEWASSET RIVER
CONNECTICUT
NEW HAMPSHIRE
MAINE
LEWISTON
AUBURN
BRUNSWICK
BATH
PLYMOUTH
PORTLAND
WINNEPESAUKEE LAKE
BRISTOL
FRANKLIN
MERRIMACK RIVER
VERMONT
NEW HAMPSHIRE
CONCORD
PORTSMOUTH
MANCHESTER
BRATTLEBORO
NEW HAMPSHIRE
MASSACHUSETTS
LOWELL

Fig. 1--Map of Androscoggin, Merrimack, and Connecticut river-basins

southerly limits are north latitude 45° 40' and 40°, respectively. About 80 per cent of the drainage-area is in Maine and 20 per cent in New Hampshire. A map of the Drainage-Area is given in Figure 1.

The Androscoggin River proper extends from sea-level at Brunswick, Maine, to Errol, New Hampshire, a distance of 166 miles, with a fall of 1,214 feet and has a drainage-area of 2,380 square miles entirely uncontrolled, except by natural storage. This is the area producing the annual flood and on which snow-surveys are made for purposes of flood-estimates.

The yield from the remaining 1,095 square miles of drainage-area is utilized to collect 29.5 billion cubic feet of stored water in six separate reservoirs. On this area snow-surveys are made to determine how much draft on storage may be made in the winter months and still obtain a maximum fill at the end of the spring runoff. This 1,095 square miles we know as the controlled area and it is utilized not only for river-regulation, but also for flood-control. In the great flood of 1936 when unprecedented flood-levels were reached, the yield from the controlled area of 1,095 square miles was practically eliminated as a source of flood-water. It comprises 32 per cent of the total drainage-area. Therefore, during flood-periods the effect of storing water on peak-flows is very great.

The annual precipitation in this area is, for the elevations between sea-level and 300 feet, an average of about 43 inches, with a maximum of 58 inches and a minimum of 29 inches. The total snowfall for the winter will range between 60 inches and 120 inches, while the snow-cover will rarely exceed 36 inches at any particular time.

Between elevations of 300 and 1,500 feet, the annual precipitation will average 39 inches with a maximum of 51 inches and a minimum of 27 inches. The total snowfall will vary from 60 inches as a minimum and 140 inches as a maximum. The snow-cover will rarely exceed 50 inches in this area at any given time.

Above 1,500 and to 3,000 feet, the annual precipitation will average about 34 inches, with a maximum of 51 inches and a minimum of 24 inches. The snow-cover will rarely exceed 60 inches and not average more than 48 inches.

The heaviest snow-measurement ever recorded in this area was 72 inches of snow with 18.5 inches of water-content. Snow-covers of 48 inches with 15 inches of water-content are not uncommon in the late spring.

On Mount Washington in the White Mountain Area, the precipitation in 1935-36 was 76 inches; in 1936-37 it was 102 inches. Higher annual rates have been recorded.

The River is developed for 275,000 horsepower of wheel-capacity, all of which the work of river-regulation serves. Water derived from snow furnishes the bulk of this power in the summer months. The snow-surveys, therefore, offer a reliable source of information on which to base production during the summer months.

Details of snow-surveys in the Androscoggin Valley

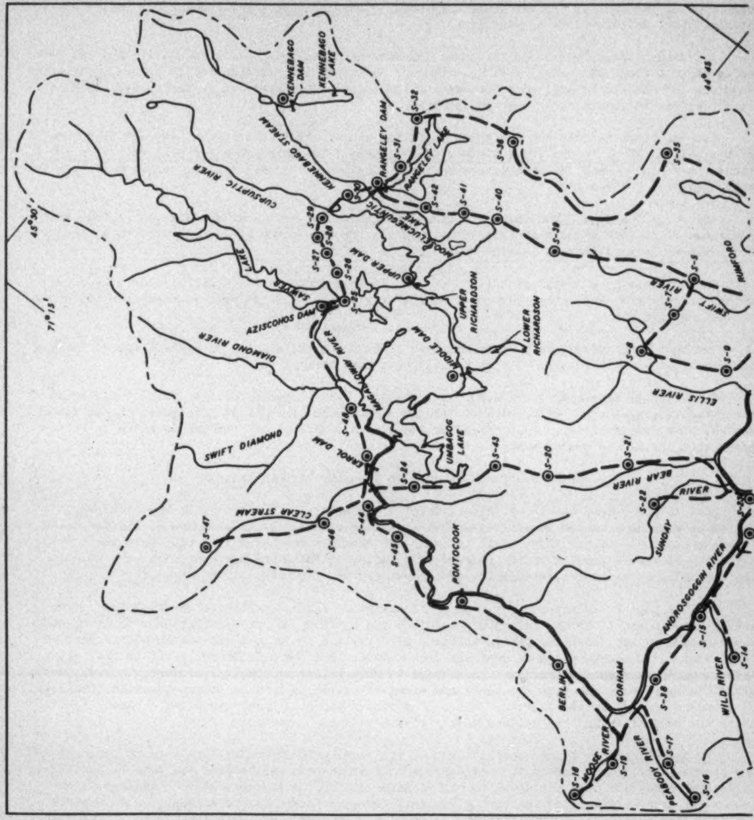
Some 50 years ago, Charles A. Mixer, Chief Engineer of the Rumford Falls Power Company, wanted to know as a matter of curiosity what the water-content of the snow was on a given date. It was typical of the man then, as it is today, to seek the truth and find it. This was the beginning of snow-surveying in the Androscoggin Valley in Maine and New Hampshire. It was also the beginning of extensive development of the water-power resources of the Valley.

In 1881, the Union Water Power Company of Lewiston, Maine, started the development of the storage-resources at the headwaters of the River and by 1912 had, in association with other companies, constructed storage-capacity totaling 29.5 billion cubic feet and taking nearly perfect control of 1,095 square miles of drainage-area. Since 1881 the demands for power in the Valley have steadily increased until water in storage is very valuable; also the commercial developments along the River have occupied the low lands along the River to such an extent that the liability of flood-damage has become serious. Zoning ordinances controlling construction in these low areas are non-existent. There flood-danger always exists.

The determination of the water-content of the snow, which normally furnishes 60 per cent of the stored water, is so important that considerable expense in determining the same is justified to determine maximum possible draft on stored water during the winter months. Likewise, since one of the major elements of the spring flood is the water-content of the snow, the snow-survey discloses the magnitude of this important element and enables a reasonable estimate of the possibilities of the spring flood being made in advance. These are the prime reasons for making snow-surveys. Their value has been fully demonstrated in this Area.

The cost of these snow-surveys is so small when compared to the cost of river-regulation and the value of the results is so great that expenditures are fully justified to attain a reasonable degree of accuracy in estimating the total water-content of the snow on both the storage-area and the uncontrolled area.

The accuracy obtainable by means of these surveys is of interest. While the surveys have been carried on for many years in a simple way, we discovered errors in our estimates of water available for storage-purposes from the snow-cover and in the total volume of spring runoff, which were, at times, very large. For this reason, the scope of the survey was materially extended until about 500 miles of traverse are now run, covering elevations from 200 feet above mean sea-level to 6,000 feet above mean sea-level. This expansion has made estimates fall within an error of about five per cent, which is sufficiently accurate for practical purposes, so that


KENNEBAGO DAM
KENNEBAGO LAKE
KENNEBAGO STREAM
CUPSUPTIC RIVER
RANGELEY DAM
RANGELEY LAKE
S-32
S-31
S-36
S-35
44°45'
S-42
S-41
S-40
S-39
MOOSELUCMEGUNTIC LAKE
S-29
S-28
S-27
S-26
S-25
45°30'
71°15'
UPPER DAM
SAWYER LAKE
AZISCOHOS DAM
DIAMOND RIVER
UPPER RICHARDSON
LOWER RICHARDSON
MIDDLE DAM
RUMFORD
S-5
S-7
SWIFT RIVER
S-8
S-9
ELLIS RIVER
MAGALLOWAY RIVER
S-48
ERROL DAM
SWIFT DIAMOND
UMBAGOG LAKE
S-43
S-20
S-21
BEAR RIVER
S-24
S-22
SUNDAY RIVER
S-47
CLEAR STREAM
S-46
S-44
S-45
PONTOCOOK
ANDROSCOGGIN RIVER
S-15
S-14
WILD RIVER
BERLIN
GORHAM
S-38
S-17
S-16
PEABODY RIVER
MOOSE RIVER
S-19
S-18

today the work, as carried out, offers a much more representative sampling of the snow-cover than ever before.

Figure 2 is a map of snow-measuring stations. Accuracy was obtained by placing one snow-measuring station for every 50 square miles of drainage-area. Practically every main stream in the Valley has a station at river-level and, wherever possible, one at a high level.

Snow-traverses are carried at three points to elevations of 4,000 to 6,000 feet to observe the effect of elevation on precipitation in that area and to serve as checks over the whole storage-area where high-elevation readings are not available. In any given section, the water-content of the snow shows an increase with increase in elevation.

A daily check of snow-cover conditions on the storage-area is in operation at Aziscohos Dam in Wilson's Mills, Maine, where daily records of temperature, depth, and water-content of the snow are obtained and the amount of water collected each spring can be, and is, measured. Such

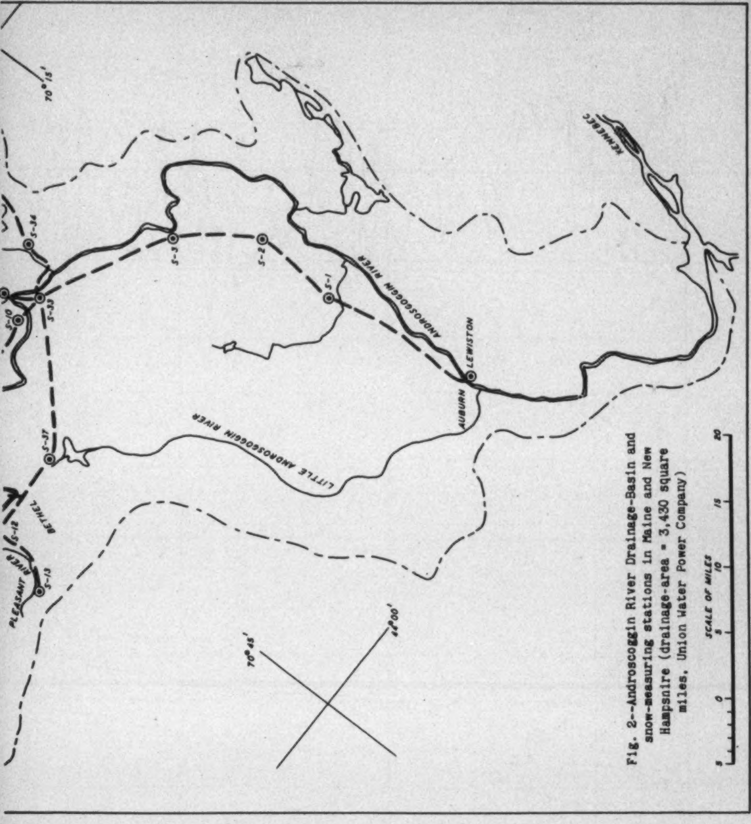
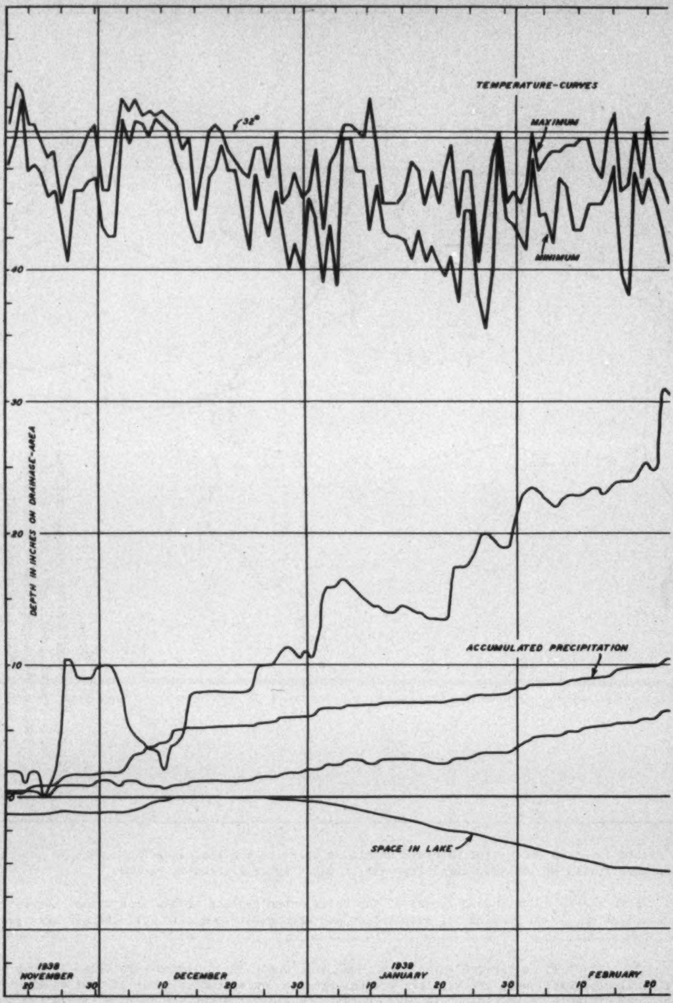

70°15'
KENNEBEC
S-34
S-3
S-2
S-1
S-33
S-10
ANDROSCOGGIN RIVER
LEWISTON
AUBURN
LITTLE ANDROSCOGGIN RIVER
S-37
BETHEL
S-12
S-13
PLEASANT RIVER
70°45'
44°00'
SCALE OF MILES
5
0
5
10
15
20

Fig. 2--Androscoggin River Drainage-Basin and snow-measuring stations in Maine and New Hampshire (drainage-area = 3,430 square miles. Union Water Power Company)

a record is shown plotted on Figure 3 submitted herewith and indicates the change in general characteristics of the snow-cover from day to day. It is a valuable record.

Figure 3 is a continuous record of the daily water-content of the snow which, together with precipitation, is to provide for evaporation and ground-water, and to fill the storage-space in Aziscohos Lake.

The curves of "water-content of the snow" and "space-in-the-lakes" are drawn to such vertical ordinates that, when the vertical ordinate to the "water-content" curves just equals the vertical ordinate to the "space-in-lake" curve, the water-content in the snow is exactly equal to the volume of water necessary to fill the empty storage-space in the reservoir at runoff of 100 per cent. Thus, a comparison of the vertical ordinates to these two curves will indicate on any date to what extent the water-content of the snow will provide full reservoirs, what the prospects are for a spring fill, and whether the reservoirs are being overdrawn or not. This



method of control applies to all lakes in the storage-system at the headwaters of the Androscoggin River.

Comparison of the "depth-of-snow" curve with the "water-content-of-the-snow" curve gives the specific gravity of the snow-cover at any given date. The specific gravity of the snow-blanket

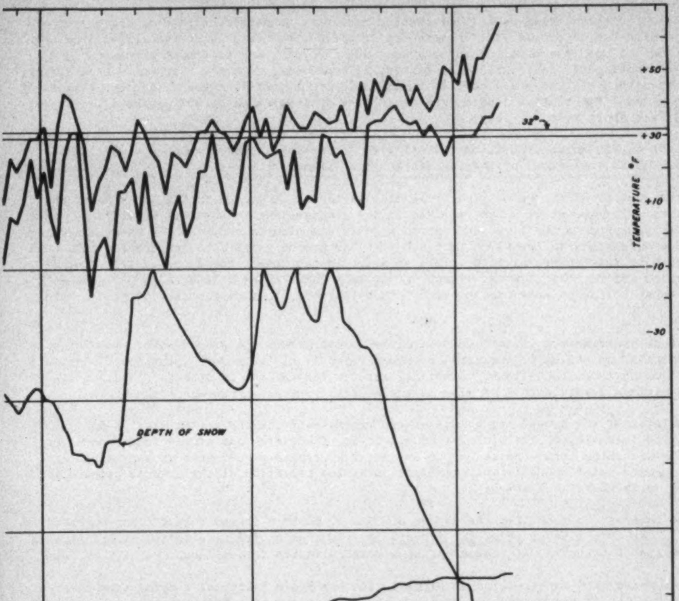


Fig. 3

is useful in estimating the capacity of the snow-blanket to absorb rain. You will note that from December 10-25, 1938, the temperature was above freezing and a thaw occurred, which filled the lake, as shown by the "space-in-lake" curve, and the response of the lake to snow-water starts when the specific gravity is about 25 per cent and moves relatively fast at a specific gravity of about 40 per cent to 50 per cent.

The curves in general give us all information necessary to determine rate of draft on the reservoirs permissible to provide full reservoirs in the spring, to provide the losses from the snow-blanket due to both evaporation and to ground-water supply, and to permit a reasonably accurate determination of the volume to be wasted, if necessary, from the reservoirs each spring. The results from this station are a very fair sample of conditions over the total storage-area of 1,095 square miles. The station itself is located on a drainage-area of 233 square miles at elevation 1,500 feet above mean sea-level.

The set of curves shows the main characteristics of the snow-cover from day to day in the winter of 1938-39 as influenced by temperature and precipitation.

The water-content of the snow, plus the precipitation as recorded, is the total water which nature supplies. The amount of water received in the storage-lake is normally about 75 per cent of this total supply up to the time that the snow-cover has disappeared. So far as we can determine--and much more study is needed on this subject--the ground appears to temporarily hold back from two inches to four inches of this volume of water in the snow. The value of this ground-water supply and its rate of flow is evident, since this constitutes a reserve supply just as much as the water in the storage-basins, with this difference, that we cannot control the rate of yield.

The essence of river-regulation and control is to supplement the ground-water yield by water drawn from the storage-basins to the limit of wheel-capacity of the several stations. Complete knowledge of ground-water conditions, therefore, reduces the hazards of storage-operations in delivering a maximum possible rate of flow to the several power-stations along the River.

The condition of the ground and volume of the ground-water in the spring exert a heavy influence on the intensity of the spring floods. It is, therefore, one of the functions of the snow-survey to determine these conditions as evidenced by frozen ground when snow-readings are taken and of ground-water conditions by examination of the condition of the several streams and inspection of wells where available.

It is of interest to note that the winter of 1939-40 shows a frozen forest-floor on March 15, 1940. Usually, at this time of year, the forest-floor is free of frost, with the exception of a thin layer of ice at the point of contact of snow-cover with the forest-floor.

In recent years, the construction of highways and the State policy of keeping them clear of snow, permits the use of the automobile over a large part of the area and assists very much in reducing time required to complete a survey. Where the highways are not available snow-shoes are the order of the day. Aside from the danger arising from blizzards and blocked roads and from driving an automobile over glare-ice, little danger exists.

The snow-testing tubes used have been developed by us to meet conditions presented in this area and consist of a six-foot aluminum tube, 2.65 inches in diameter at the cutting edge.

The usual weighing scale is used and the water-content of the sample determined from a special table showing the water-equivalent of the snow. Experiments are now being made with tubes up to 12 inches in diameter, to determine the possible error due to using a tube of a certain diameter. To date, no appreciable error has been found which would cast doubt on the integrity of the readings from the 2.65-inch tube used by us.

The individual snow-measuring station along the traverse is selected and prepared with much care. It is selected, first, with the idea of being as representative as possible of the conditions of forest-cover in that particular drainage-area. The station is marked well above the snow-line in large painted letters, easily seen from the traveled road. The ground at the station is prepared during the summer months by leveling off the surface of the forest-floor and covering the same with the decaying material found on the forest-floor in that vicinity. The errors due to an unlevel base are thus eliminated and natural conditions restored, so far as possible. [The method and apparatus used in taking these snow-measurements are explained in the paper submitted by Paul Webster Bean and Frederick A. Bendtsen, pp. 916-919.]

In recent years we are developing our study of the snow-cover beyond the mere fact of determining its water-content. So far as studies on the subject have come to our attention, much more information of the physical characteristics of the snow is needed and is essential in flood-studies and valuable in storage-operations.

To this end the individual sample core of snow is studied under as strong a glass as can be used and its general structure is noted and described in the notes in full detail. The texture and size of the crystals seem to indicate the extent to which the snow-cover may be expected to absorb the spring rains, and also the extent to which degree-days above freezing will, in the spring, affect the capacity of the snow-cover to hold the spring rains. This feature of the work is new, but gives promise of valuable advance information of the intensity of flood-runoff to be expected under conditions of precipitation and degree-days above freezing which may exist at the time of the spring break-up. This phase of the snow-survey work seems to offer valuable information to the river-engineer.

The snow-surveying party also measures the ice-cover in the main River and on the lakes each year. In this region, the danger arising from ice-jams in the rivers is a very real one, and data on the thickness of the ice-cover and its physical condition present valuable information in estimating possible flood-conditions.

In utilizing the results obtained from the snow-surveys we proceed as follows:

For determining flood-estimates, the total drainage-area is subdivided into sections according to elevation, with the results in square miles of drainage-area, between given elevations above mean sea-level. The sheet used for this purpose above Rumford, Maine, is given on page 854. In brief, the water-content of the snow as obtained from the snow-survey is applied to the area existing at that elevation which the snow-measurement is assumed to control. Smaller drainage-areas are estimated by comparison with snow-traverses to high elevations if actual measurements are not available. There results an estimate of the total volume of water in the snow in cubic feet on important secondary watersheds before the spring rains start.

Daily records of precipitation determine how much this volume is increased by added precipitation after snow-surveys become impractical because of traveling conditions. Temperature-records indicate the rate of warming up. We thus have an estimate of the probable spring flood as to time and magnitude. The essential fact is, however, furnished by the snow-survey. The results obtained possess a reasonably high degree of accuracy. Their value in the great flood of 1936 was amply demonstrated.

The method used in computing the water to be expected in the storage-reservoirs is the same, but the results obtained are capable of more accurate measurements because the capacities of the several reservoirs are known. The survey itself has proved not only a valuable, but a thoroughly reliable guide to winter use of stored water in regulating the flow of the River.

The accuracy of estimates based on the results of the snow-surveys depends very largely on the number of readings taken on the area, and whether such readings are representative of conditions in that particular area. We expect to obtain greater accuracy with the coming years by a continual relocation of snow-measuring stations where and when the need becomes evident for any cause whatsoever. This requires time and study, but the value of water for manufacturing purposes and flood-danger make the study well worth the expenditure. The cost appears to be about $0.12 per mile of traverse, of which the automobile costs $0.10 per mile.

The cost of river-regulation is about $60,000 per year, most of which is taxes. The annual cost of snow-surveys will not exceed $1,000 as an average figure, although the cost will vary with existing conditions. Surveys are made every 30 days during the winter and more often if precipitation in the form of rain or heavy snow occurs. The annual cost of snow-surveys is relatively insignificant compared to benefits accruing therefrom.

Utilization of snow-surveys for storage-purposes

The snow-survey furnishes accurate base data on which an estimate can be made as to the probability of filling any or all of the six separate storage-reservoirs making up the Rangeley Storage System. As an average figure, the snow supplies approximately 70 per cent of the water stored in the system at the end of the spring runoff, the other 30 per cent being derived from precipitation in April and May, the reservoirs being normally full about May 30.

The snow-surveys being taken in the valleys of the main streams feeding the lakes and being supplemented by snow-surveys carried to elevation of 4,000 feet provide a reasonably accurate estimate of water-content in the drainage-area of each feeder at the elevation taken. The snow-surveys carried to elevation of 4,000 feet enable corrections to be applied to those elevations of the drainage-area not reached by the snow-traverse. This closely indicates the total water-content of the snow at different elevations in the watershed.

Where the topographic maps are available, the areas in a given drainage-basin between two contours, say 1,500 to 2,000, are planimetered and determined in square miles. Where the topographic maps are not available, the areas are estimated between contours from such maps as are available.

Multiplying the drainage-area in square feet by the water-content of the snow, there results a volume of water in cubic feet which would result with runoff of 100 per cent. In practice, the yield from the drainage-area is about 75 per cent of the water-content of the snow in the average year and appears to be a safe figure to use in storage-operations.

The 75 per cent runoff-factor for a water-content of the snow of 12 inches allows three inches for ground-water supply and for evaporation. We are of the opinion that this allowance should never be less than two inches, whatever the water-content of the snow. We are also convinced that a quick spring break will result in about two inches of ground-water. This subject is being studied by us.

Conditions of evaporation vary greatly from year to year. In an average year we suffer no great loss from this source, but sometimes conditions of evaporation exist which would cause losses estimated as high as three inches, although they have never been measured. The period of time during which this loss occurs is about five weeks from the time of the spring break-up until the snow-cover has disappeared and often is a shorter period of time.

The capacity of the ground to hold water in temporary storage and the rate of inflow are subjects of constant study on our part and, to date, little of real truth has emerged. It is, however, next to the water-content of the snow in importance in storage-operations. We feel sure that this drainage-area will absorb two inches of water before any appreciable runoff commences. We believe the capacity of the ground is greater, but have never had definite proof of the same.

Ground-water studies are made by observing water-level in wells and the yield of certain drainage-areas in dry periods. The subject is important and worthy of more study.

In operating the storage-reservoirs in winter, the water-content of the snow being periodically determined, we can balance the water-content of the snow against vacant capacity in the reservoirs and regulate the draft from storage intelligently.

For example, if the water-content of the snow indicates a volume of 20 billion cubic feet of water at 75 per cent runoff and the vacant capacity in the reservoirs is 22 billion at a given time, we can continue our draft on storage with confidence of filling the reservoirs with normal conditions of precipitation prevailing in the spring. There are, of course, many variations from conditions stated in the example; the point is that the water-content of the snow is sufficiently large in relation to the storage-capacity that a considerable degree of flexibility is given to storage-operations which never existed before the snow-surveys were available.

The desired rate of regulated flow is obtained by delivering a fixed rate of flow at Berlin, New Hampshire, which, in turn, is accomplished by supplementing the yield from the uncontrolled area by draft on the storage-reserve when necessary.

The storage-reserve must be operated to maintain a maximum low-water flow during the winter and in the dry months of summer. Draft from storage must, therefore, be regulated in the light of storage-reserves available to carry through both summer and winter. Fall rains, on the average, provide little increase in stored water.

The basic requirement of river-regulation calls for the maintenance of the highest minimum flow possible with the reserve-water available. This requires that draft on storage must be no greater than the reserve will permit and, at the same time, have only sufficient space in the reservoirs to receive the water-content of the snow, plus precipitation and without waste from the storage-reservoirs, at the close of the spring runoff.

The rate of draft on storage is determined by means of a curve showing the weekly loss from storage for a given rate of flow at Berlin, New Hampshire. By increasing or diminishing the flow at Berlin, New Hampshire, it is possible to force this curve in any desired direction from week to week. The water-content of the snow, plus average conditions of precipitation, indicate very definitely where the draft-curve must plot when the spring break comes. The snow-survey makes the point of maximum draft fall within very small limits. Without the snow-survey, the regulatory work is very inefficient and, in many years, wasteful.

Utilization of snow-surveys in estimating floods

Utilization of the snow-surveys in estimating flood-flows is possible because the flood-producing characteristics of the Androscoggin River are well defined and based on 60 years of record. The water-content of the snow will account for from 50 per cent to 80 per cent of the total spring runoff during periods of severe intensity of flow.

Subject to minor variations, the shape of the hydrograph of flood-flow is now widely different from year to year for floods of greater than average magnitude and the total volume of water to be passed by a given station can easily be determined for a given period of time. Since the water-content of the snow furnishes from 50 per cent to 80 per cent of this flood-water, an approximate estimate of probable flood-conditions is possible for a considerable period of time prior to the spring break. Experience in this Valley indicates that if on March 1 there is a water-content of the snow of 20,000,000 cubic feet per square mile on the uncontrolled area, an average flood is to be expected, with little danger of damage. When the water-content of the snow rises to 30,000,000 cubic feet per square mile, serious flood-conditions are to be expected and warnings may be properly broadcast.

The method of computing the total volume of water in the snow is the same as previously indicated, with this exception, that those parts of the drainage-area between the important contours are based almost wholly on topographic maps. Such a map is the map by Thomas [see pp. 851 and following].

With wide variations in elevation throughout the area and a marked variation in water-content of the snow, the data furnished by this type of information add materially to the accuracy of the estimate. Also knowledge of the probable yield from areas of quick runoff as shown by the record of past years is valuable in estimating the magnitude of peak-flows.

During flood-operations, knowledge is most often sought as to the time before a given elevation of flood-water is reached and how high the water will ultimately rise. The water-content of the snow, with records of conditions of precipitation, temperature, and ice, provide a reasonable answer, close enough for most conditions. During severe flood the ice-jams produce the greatest element of uncertainty in making predictions and in 1936 made accurate estimates nearly impossible.

The method of predicting is based on hourly readings of flow at Berlin, New Hampshire, Rumford Falls, and Lewiston--all being gaging-stations along the River.

Starting with the first sign of extensive runoff, three hydrographs of flow are prepared, plotting flow at each station against time in hours. This determines the shape of the rising end of the flood-curve and usually 24 hours will establish very closely the average hourly increase as the flood advances toward its peak.

With the water-content of the snow known and precipitation added to the water-content of the snow, we know approximately the total volume of water to be passed by a given station. Knowing also from experience that a large percentage of this water will pass in a limited number of days, we can obtain an average flow for the period to pass this volume of water. Knowing further that the peak will approximate from 1-1/2 to 2-1/2 times the average, we get an approximate peak-flow occurring at a point of time indicated by previous plottings of actual flows from the several stations.

These estimates are based on conditions of precipitation and temperature prior to a given hour. If more precipitation is obtained, the estimates must be revised from hour to hour and new estimates of flood-heights made.

The furnishing of estimates along 160 miles of river calls for much preparatory work, the needs of which are seldom evident in all details until one has been through a major flood, accompanied by heavy damage. Our experience indicates that to derive maximum benefit, telephone-communications to key observers well out of the reach of the water should be arranged for beforehand, although they may not be needed for years. Also, the observers should be acquainted with the needs of the office and render reports of water-stages based on prearranged gages. Aerial maps are invaluable and of the greatest aid in sending out warnings, because rates of flow causing damages can be plotted thereon and information from the observers may be intelligently interpreted.

If the Federal Government would spend one per cent of its flood-control appropriations in preparing complete aerial maps of these rivers, flood-warnings should prevent loss of life and permit more intelligent town-planning to prevent damage of property. The maps should be available at all offices sending out flood-warnings.

Flood-work of the nature herein described would be impossible without the snow-surveys, and they do furnish data of sufficient weight and accuracy to make possible accurate estimates of flood-conditions for a large percentage of time.

The flood of 1936

At the urgent suggestion of Dr. Church, the following description of our forecasting of the flood of 1936, so far as I can recall the same, is included.

On March 1, 1936, a very complete snow-survey of the Androscoggin Basin indicated approximately 10 inches of water in the snow as an average figure for the low levels, and at higher elevations, from 12 inches to 18 inches of water in the snow. As high elevations predominate in the uncontrolled drainage-area, it was clearly evident that if heavy precipitation, accompanied by high temperatures, was obtained, a flood of major magnitude could be expected.

The snow-survey showed unprecedented conditions of water-content of the snow and a volume of flood-water to pass Lewiston of not less than 60 billion cubic feet, which was also unprecedented for this date and pointed to serious high water and flood-damages.

The snow-cover extended far to the south, was heavy, and showed little sign of melting. It seemed obvious to us that this condition clearly pointed to a sudden break, which actually occurred. Severe flood-conditions existed prior to March 13, 1940, the date of the flood in this Valley.

Recognizing the danger, we took it on ourselves to notify the State Highway Commission that they might clear their culverts, the railroads that they might make such plans as they saw fit, as also the industries along the river--all of which are located on the bank of the river--and low-lying mercantile establishments along the River. This was done between March 1 and March 5. Tne flood of 1936 occurred March 13 to 20.

A stationary high-pressure cold-front area stalled over the Gulf of St. Lawrence and a warm current of tropical air flowing north from the Gulf of Mexico on March 13, provided the other necessary elements to produce the greatest flood in this area within the memory of man.

As to the magnitude of the flood, it is estimated to have reached more than 200,000 cfs from 2,000 square miles. The advance of the peak of the flood down-river was clearly evident by loss of all telephone-service as the peak-flow passed the several towns.

In the White Mountain Area approximately 20.3 inches of rain fell on a snow-cover with a water-content of 18 inches. Practically the total area received a rainfall approximating ten inches or more on a snow-cover containing never less than ten inches of water.

These severe conditions continued for nearly a week and considerably more than 120,000,000 cubic feet of water passed Lewiston. The River at Lewiston rose close to 40 feet at the peak-flow.

While no part of our obligations, we, of necessity, had to assume the position of advisor to the whole Valley and for one week, 24-hour-a-day service was rendered those in trouble and they were many.

We would not have missed the experience for any money but we would not care to go through it again for $1,000,000. One gets a real thrill, sitting in front of a flow greater than normally passes Niagara Falls passing down this River with a normal average flow of 1,800 cubic feet per second.

Damages ran into millions of dollars but there was no loss of life due to the flood. A number were so frightened they died of heart-failure. That there was no loss of life I attribute wholly to the knowledge of the probable magnitude of the flood derived chiefly from results of the snow-survey.

Union Water Power Company,
Lewiston, Maine

DISCUSSION

PHILIP W. THOMAS (Engineer, Rumford Falls Power Company, Androscoggin Basin, Maine; communicated)--Figure 1 shows the graph we have adopted to show the probable variation in precipitation as the latitude and elevation of recording stations vary. The data and compilations upon which Figure 1 is based are given in the accompanying Tables. One Table gives the subdivided areas of our contour-map and the corresponding multiplying-factor to apply in arriving at the average yield for the particular area, taking into consideration the correction for latitude and elevation, as well as the size of the area in which the precipitation-station is located.

Since making this last tabulation we have rearranged the areas and you will find the final tabulation and results incorporated on the contour-map of our drainage-basin as reproduced in Figure 2.

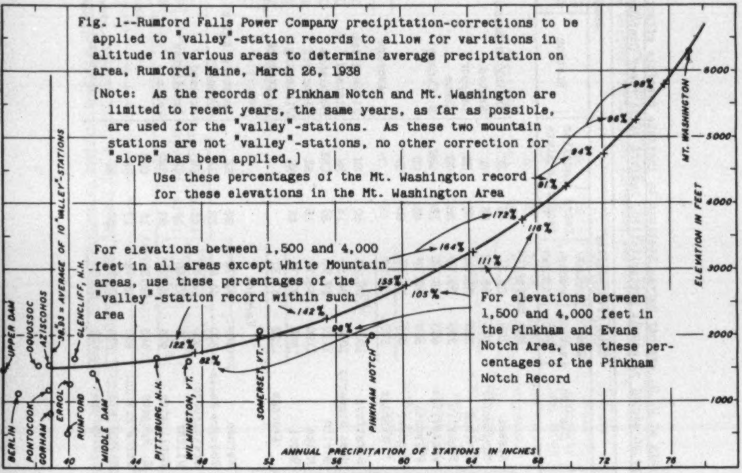


Fig. 1--Rumford Falls Power Company precipitation-corrections to be applied to "valley"-station records to allow for variations in altitude in various areas to determine average precipitation on area, Rumford, Maine, March 26, 1938

[Note: As the records of Pinkham Notch and Mt. Washington are limited to recent years, the same years, as far as possible, are used for the "valley"-stations. As these two mountain stations are not "valley"-stations, no other correction for "slope" has been applied.]

Use these percentages of the Mt. Washington record for these elevations in the Mt. Washington Area

For elevations between 1,500 and 4,000 feet in all areas except White Mountain areas, use these percentages of the "valley"-station record within such area

For elevations between 1,500 and 4,000 feet in the Pinkham and Evans Notch Area, use these percentages of the Pinkham Notch Record

UPPER DAM
OQUOSSOC
AZISCOHOS
38.93 = AVERAGE OF 10 "VALLEY"-STATIONS
GLENCLIFF, N.H.
BERLIN
PONTOCOOK
GORHAM
ERROL
RUMFORD
MIDDLE DAM
PITTSBURG, N.H.
WILMINGTON, VT.
SOMERSET, VT.
PINKHAM NOTCH
MT. WASHINGTON
122%
82%
142%
96%
155%
105%
164%
111%
172%
116%
91%
94%
96%
98%
40
44
48
52
56
60
64
68
72
76
ANNUAL PRECIPITATION OF STATIONS IN INCHES
1000
2000
3000
4000
5000
6000
ELEVATION IN FEET

Relation of eastern-slope and western-slope exposure stations to "valley"-stations precipitation-records, to determine corrections to be applied to obtain average precipitation for areas with less than 1,500-foot elevation

Summary of data taken from United States Weather Bureau records as published in Sections 84 and 85, "Climatic Summary of United States"

State	Exposure-station			
	Eastern-slope elevation		Western-slope elevation	
	0-1,000	1,000-1,640	0-1,000	1,000-1,640
New Hampshire	$\frac{41.63}{37.50}$ = 1.11	$\frac{45.65}{37.37}$ = 1.22	$\frac{40.66}{37.50}$ = 1.09	$\frac{40.83}{37.37}$ = 1.09
Vermont	$\frac{38.76}{35.62}$ = 1.09	$\frac{42.26}{35.62}$ = 1.19	$\frac{36.60}{35.62}$ = 1.03	$\frac{38.66}{35.62}$ = 1.08
Maine	$\frac{37.38}{38.62}$ = 0.97	$\frac{37.71}{36.45}$ = 1.03	none; use 1.00	$\frac{45.21}{36.45}$ = 1.24
Averages	1.06	1.15	1.04	1.14
Correction		1.10		1.09

Tabulation of precipitation-data at U. S. Weather Bureau Stations to indicate possible effect of altitude and slope-exposure on amount of annual precipitation, Rumford Falls Power Company

Eastern-slope exposure					Main river-valley					Western-slope exposure				
Station	Elevation, feet	Annual precip., inches	Years record	Location in State	Station	Elevation, feet	Annual precip., inches	Years record	Location in State	Station	Elevation, feet	Annual precip., inches	Years record	Location in State
						New Hampshire								
Durham	83	38.73	36	ES	Nashua	125	39.31	46	SC	Arlington (Mass.)	168	40.34	20	SE
Brookline	250	41.88	25	SC	Manchester	171	38.32	55	SC	Newton	200	39.31	28	SE
Peterboro	744	44.28	11	SC	Concord	350	35.80	73	SC	Lakeport	500	42.15	74	CE
					Franklin	390	39.50	28	CC	Keene	550	37.59	33	SW
					Woodsville	450	35.14	13	CNW	N. Conway	575	43.91	13	CNE
					Plymouth	500	39.16	42	CC					
					Hanover	603	35.25	90	CW					
Average	360	41.63			Average	370	37.50			Average	398	40.66		
Lincoln	1200	45.65	10	CNC	Stratford	1000	38.22	50	NW	Fitzwilliam	1100	42.91	11	SW
					West Stewarts	1050	34.16	16	NW	Alstead	1120	40.12	29	SW
					Berlin	1110	37.96	30	CNE	Bethlehem	1440	35.52	37	CNW
					Milan	1190	38.76	15	NE	Glencliff	1650	40.36	21	CW
					Errol	1260	37.76	45	NE	Pittsburg	1660	45.32	13	NW
					Average	1122	37.37			Average	1394	40.83		
						Vermont								
Newfane	450	46.14	15	SE	Vernon	228	41.74	33	SE	Enosburg Falls	422	39.85	39	NW
St. Johnsbury	711	34.68	37	NE	Bellows Falls	300	34.84	22	SE	Cornwall	504	31.85	43	CW
Northfield	765	32.88	28	CNC	Brattleboro	330	39.80	45	SE	Rutland	610	36.03	15	CC
Woodstock	800	38.31	62	CE	Wilder	370	32.46	10	CE	Bennington	840	37.71	10	SW
Cavendish	800	38.12	27	CSE	Burlington	404	32.28	98	CNW	Wells	900	37.55	26	CSW
Mays Mill	850	42.45	17	SE	E. Ryegate	443	32.35	16	CNE					
					White Riv.Jc.	490	33.78	17	CE					
					Bloomfield	930	37.72	23	NE					
Average	730	38.76			Average	437	35.62			Average	655	36.60		

Tabulation of precipitation-data at U. S. Weather Bureau Stations to indicate possible effect of altitude and slope-exposure on amount of annual precipitation, Rumford Falls Power Company--Concluded

Eastern-slope exposure					Main river-valley					Western-slope exposure				
Station	Ele-vation, feet	Annual precip., inches	Years record	Location in State	Station	Ele-vation feet	Annual precip., inches	Years record	Location in State	Station	Ele-vation feet	Annual precip., inches	Years record	Location in State
					Vermont--concluded									
Jacksonsville	1000	45.12	28	SC						Garfield	1300	38.66	16	NC
S.Londonderry	1000	37.35	17	SC						Somerset	2080	51.88	19	SC
Chelsea	1070	35.78	44	CE										
Whitingham	1450	45.73	8	SC										
Wilmington	1640	47.35	9	SC										
Average	1232	42.26												
					Maine									
Houlton	364	30.97	32	ECN	Madison	257	42.62	28	CW					
Danforth	386	36.05	27	ECN	N. Bridgton	450	43.08	36	SW					
Millinocket	388	42.35	31	CNE	Rumford	505	39.34	37	CW					
Farmington	425	42.19	42	CW	Van Buren	510	36.38	22	NE					
Eustis	450	35.33	16	CW	The Forks	570	36.94	19	CW					
					Presque Isle	606	33.38	17	NE					
Average	402	37.38			Average	483	38.62							
Jackman	1180	37.71	9	CNW	Greenville	1140	41.09	29	CN	Mayfield	1000	45.21	14	CCW
					Middle Dam	1430	34.44	26	WC					
					Upper Dam	1484	32.77	45	WC					
					Aziscohos	1528	36.50	19	WC					
					Oquossoc	1534	37.48	20	WC					
					Average	1423	36.45							

Notes: Data from "Climate summary of United States," Section 84 for New Hampshire and Vermont, Section 85 for Maine [U. S. Weath. Bur., Dep't Agric.]; stations influenced by location near seacoast are purposely omitted. Abbreviations: ES = east south; SC = south central; CNC = central north central; CE = central east.

Corrections to apply to precipitation-records of observation-stations to allow for variations in altitude and slope-exposures, Rumford Falls Power Company, Rumford, Maine, March 29, 1938

Areas in square miles at given elevations above sea-level

Area and station		Altitude-range in feet above sea-level												Total
		500-1000	1000-1500	1500-2000	2000-2500	2500-3000	3000-3500	3500-4000	4000-4500	4500-5000	5000-5500	5500-6000	6000-6500	
No.1, Rumford	a	71.25	33.25	7.62	0.63	.....	.....	.....	.....	.....	.....	.....	.....	112.75
	b	1.05	1.05	1.22	1.42	.....	.....	.....	.....	.....	.....	.....	.....	1.06
	c	74.81	34.91	9.30	0.89	.....	.....	.....	.....	.....	.....	.....	.....	119.52
No.2, South Andover	a	53.19	80.97	56.65	30.50	7.11	2.89	0.63	.....	.....	.....	.....	.....	231.94
	b	1.05	1.05	1.22	1.42	1.55	1.64	1.72	.....	.....	.....	.....	.....	1.16
	c	55.84	85.02	69.11	43.31	11.02	4.74	1.08	.....	.....	.....	.....	.....	269.05
No.3, Gilead	a	55.43	55.76	37.00	24.87	16.38	6.00	0.87	0.13	.....	.....	.....	.....	196.44
	b	1.05	1.05	1.22	1.42	1.55	1.64	1.72	1.72	.....	.....	.....	.....	1.19
	c	58.20	58.55	45.14	35.31	25.39	9.84	1.50	0.22	.....	.....	.....	.....	233.76
No.4, Pinkham Notch	a	.....	.....	31.00	24.75	17.62	14.88	8.50	2.37	0.38	.....	.....	.....	99.50
	b	.....	.....	0.82	0.96	1.05	1.11	1.16	1.20	1.24	.....	.....	.....	0.98
	c	.....	.....	25.82	23.76	18.50	16.52	9.86	2.84	0.47	.....	.....	.....	97.51
No.5, Mt.Washington	a	.....	.....	.....	.....	.....	.....	.....	2.25	2.75	1.00	0.37	0.13	6.50
	b	.....	.....	.....	.....	.....	.....	.....	0.91	0.94	0.96	0.98	0.98	0.94
	c	.....	.....	.....	.....	.....	.....	.....	2.05	2.59	0.96	0.36	0.13	6.11
No.6, Gorham	a	11.38	26.75	10.74	7.01	3.37	0.63	0.25	.....	.....	.....	.....	.....	60.13
	b	1.00	1.00	1.22	1.42	1.55	1.64	1.64	.....	.....	.....	.....	.....	1.13
	c	11.38	26.75	13.10	9.95	5.22	1.04	0.41	.....	.....	.....	.....	.....	67.95
No.7, Berlin	a	1.12	13.32	8.43	2.75	0.13	.....	.....	.....	.....	.....	.....	.....	25.75
	b	1.00	1.00	1.22	1.42	1.55	.....	.....	.....	.....	.....	.....	.....	1.12
	c	1.12	13.32	10.28	3.91	0.20	.....	.....	.....	.....	.....	.....	.....	28.84
Rumford, uncontrolled	a	192.37	210.05	151.44	90.51	44.61	24.40	10.25	4.75	3.13	1.00	0.37	0.13	733.01
No.8, Berlin	a	.....	30.75	31.62	7.63	5.12	1.50	0.13	.....	.....	.....	.....	.....	76.75
	b	.....	1.00	1.22	1.42	1.55	1.64	1.72	.....	.....	.....	.....	.....	1.18
	c	.....	30.75	38.58	10.83	7.94	2.46	0.22	.....	.....	.....	.....	.....	90.57
No.9, Pontocook	a	.....	73.12	51.00	12.75	2.87	0.13	.....	.....	.....	.....	.....	.....	139.87
	b	.....	1.00	1.22	1.42	1.55	1.64	.....	.....	.....	.....	.....	.....	1.13
	c	.....	73.12	62.22	18.11	4.45	0.21	.....	.....	.....	.....	.....	.....	158.05
No.10, Errol	a	.....	47.86	49.25	40.75	11.13	2.63	.....	.....	.....	.....	.....	.....	151.62
	b	.....	1.06	1.22	1.42	1.55	1.64	.....	.....	.....	.....	.....	.....	1.25
	c	.....	50.73	60.09	57.87	17.25	4.31	.....	.....	.....	.....	.....	.....	189.53
No.11, Aziscohos	a	.....	13.87	51.75	64.50	20.62	3.25	0.13	.....	.....	.....	.....	.....	154.12
	b	.....	1.00	1.22	1.42	1.55	1.64	1.72	.....	.....	.....	.....	.....	1.34
	c	.....	13.87	63.13	91.59	31.96	5.33	0.22	.....	.....	.....	.....	.....	206.52
Berlin, uncontrolled	a	.....	165.60	183.62	125.63	39.74	7.51	0.26	.....	.....	.....	.....	.....	522.36
No.12, Middle Dam	a	.....	57.93	75.75	13.38	6.12	2.63	0.37	0.13	.....	.....	.....	.....	156.31
	b	.....	1.00	1.22	1.42	1.55	1.64	1.72	1.72	.....	.....	.....	.....	1.18
	c	.....	57.93	92.42	19.00	9.48	4.31	0.64	0.22	.....	.....	.....	.....	184.45
No.13, Upper Dam	a	.....	35.68	40.75	38.13	12.37	0.50	0.13	.....	.....	.....	.....	.....	127.56
	b	.....	1.00	1.22	1.42	1.55	1.64	1.64	.....	.....	.....	.....	.....	1.25
	c	.....	35.68	49.72	54.14	19.17	0.82	0.21	.....	.....	.....	.....	.....	159.45
No.14, Aziscohos	a	.....	3.25	115.49	117.12	31.25	3.01	0.25	.....	.....	.....	.....	.....	270.37
	b	.....	1.00	1.11	1.42	1.55	1.64	1.72	.....	.....	.....	.....	.....	1.30
	c	.....	3.25	128.19	166.31	48.44	4.94	0.43	.....	.....	.....	.....	.....	351.48
No.15, Oquossoc	a	.....	18.29	107.01	88.88	34.24	13.38	2.01	.....	.....	.....	.....	.....	263.81
	b	.....	1.00	1.11	1.42	1.55	1.64	1.72	.....	.....	.....	.....	.....	1.29
	c	.....	18.29	118.78	126.21	53.07	21.94	3.45	.....	.....	.....	.....	.....	340.31
Lake, controlled	a	.....	115.15	339.00	257.51	83.98	19.52	2.76	0.13	.....	.....	.....	.....	818.05

a = area in square miles; b = multiplier; c = equivalent area in square miles.

Note: For locations of areas see Figure 2.

NOTES:

Area-numbers are located in center of Areas and marked "⑤"

Weather-data stations are marked "● **Middle Dam**"

Contours marked in hundreds of feet, thus, contour marked "15" is contour 1500

This sheet was made by reduction from U.S.G.S. Topographical maps, showing only 500-foot contours

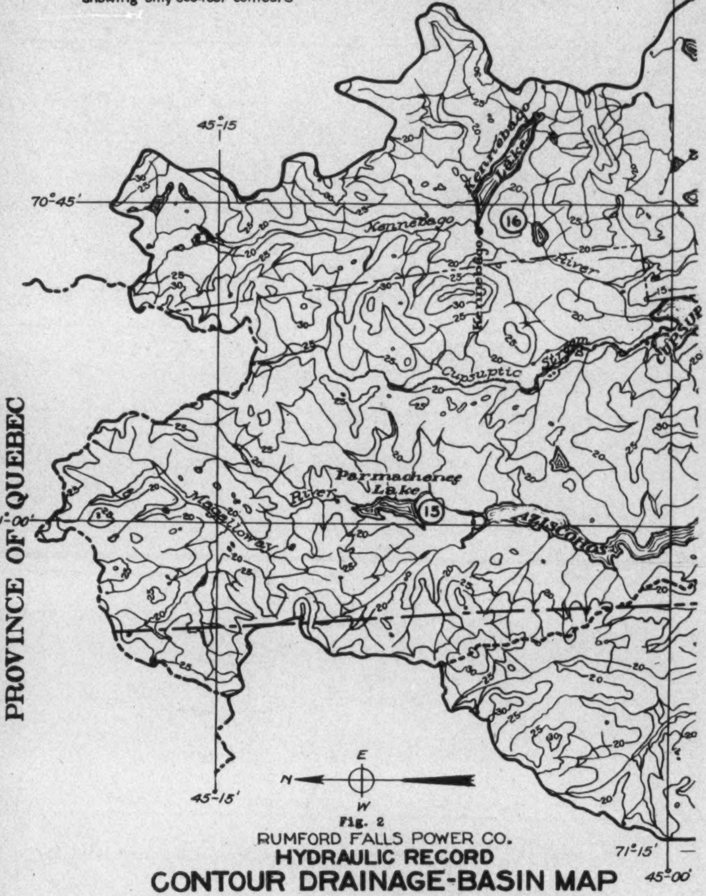

45°15'
70°45'
71°00'
71°15'
45°00'
45°15'
PROVINCE OF QUEBEC
Kennebago Lake
Kennebago
Kennebago
River
16
Cupsuptic Stream
CUPSUP
Parmachenee Lake
15
Magalloway
River
AZISCOHOS
N
E
W
20
25
30

Fig. 2

RUMFORD FALLS POWER CO.

HYDRAULIC RECORD

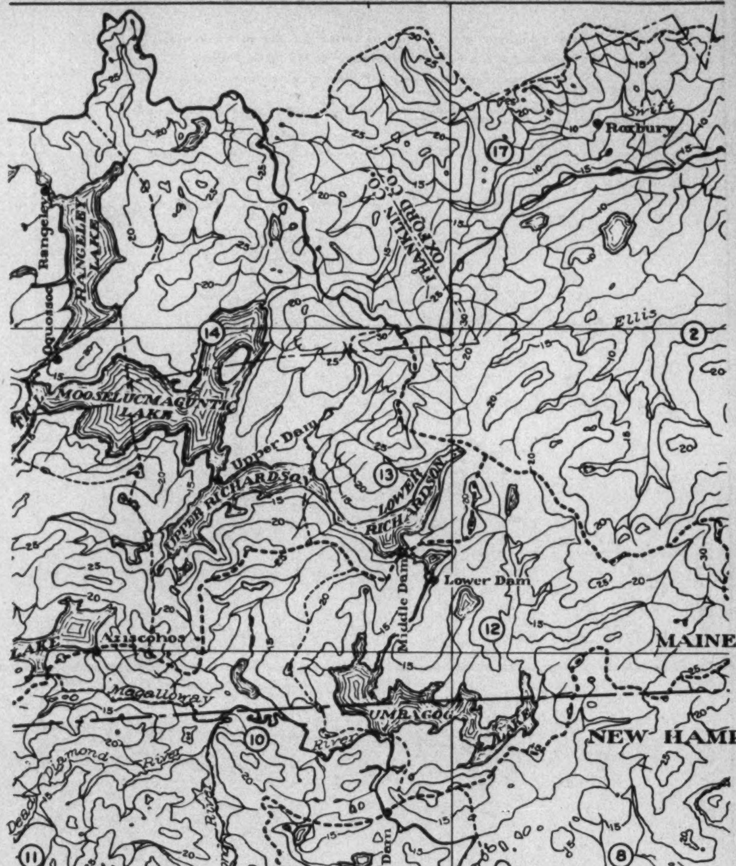
CONTOUR DRAINAGE-BASIN MAP

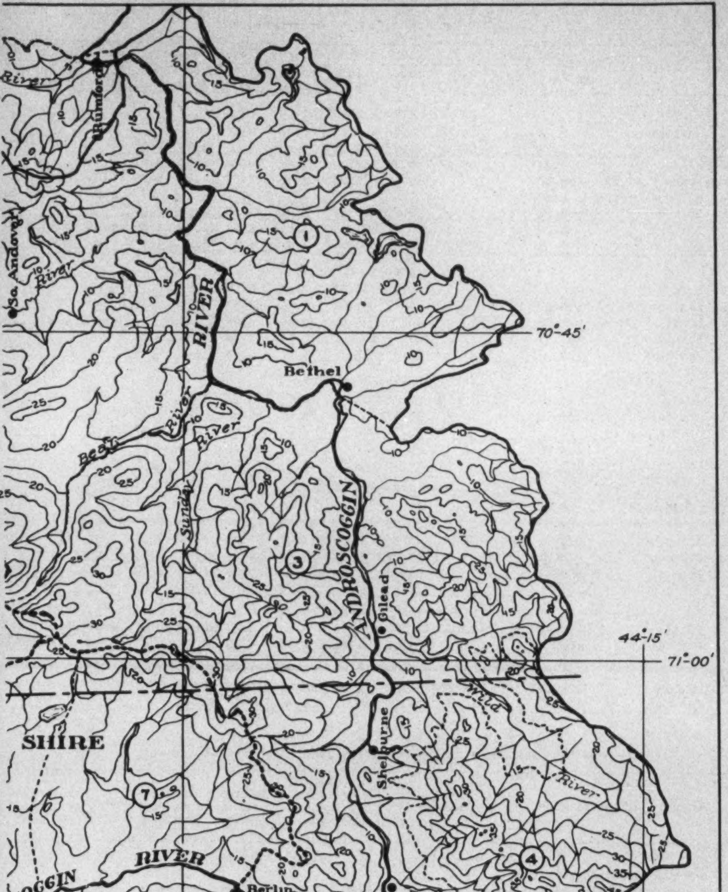
ANDROSCOGGIN RIVER ABOVE RUMFORD, MAINE

CONTOUR-INTERVAL, 500 FEET

1 0 1 2 3 4 5

Scale of Miles


Rangeley
RANGELEY LAKE
Oquossoc
Roxbury
Swift
17
FRANKLIN CO.
OXFORD CO.
Ellis
2
14
MOOSELUCMAGUNTIC LAKE
Upper Dam
UPPER RICHARDSON
13
LOWER RICHARDSON
Lower Dam
Middle Dam
12
MAINE
Aziscohos
LAKE
Magalloway
UMBAGOG
LAKE
River
10
NEW HAMP
Diamond
River
Dead
Swift
Diamond
River
11
Errol Dam
8
9
ANDROS
Pontocook Dam
44°45'


River
Rumford
So. Andover
River
RIVER
①
70°-45'
Bethel
Bear River
Sunday River
③
ANDROSCOGGIN
Gilead
44°-15'
71°-00'
Wild River
SHIRE
Shelburne
⑦
RIVER
COGGIN
Berlin
⑥
Gorham
Peabody River
Moose
④
71°-15'
Pinkham Notch
44°-15'
Mt. Washington
⑤
44°-30'
River

Sub-divided tabulation of drainage-area

Area	Station	Area sq. mi.	Areas in sq. miles between various elevations above sea-level in feet										
			0-500	500-1000	1000-1500	1500-2000	2000-2500	2500-3000	3000-3500	3500-4000	4000-4500	4500-5000	5000 +
	Rumford Area--uncontrolled												
1	Rumford	112.75		71.25	33.25	7.62	0.63						
2	S. Andover	231.94		53.19	80.97	56.65	30.50	7.11	2.89	0.63			
3	Gilead	196.44		55.43	55.76	37.00	24.87	16.38	6.00	0.87	0.13		
4	Pinkham Notch	99.50				31.00	24.75	17.62	14.88	8.50	2.37	0.38	
5	Mt. Washington	6.50									2.25	2.75	1.50
6	Gorham	85.88		12.50	40.07	19.17	9.76	3.50	0.63	0.25			
	Totals	733.01		192.37	210.05	151.44	90.51	44.61	24.40	10.25	4.75	3.13	1.50
	Per cent	100		26.2	28.7	20.7	12.4	6.1	3.3	1.4	0.6	0.4	0.2
	Berlin Area--uncontrolled												
7	Berlin	76.75			30.75	31.62	7.63	5.12	1.50	0.13			
8	Pontocook	139.87			73.12	51.00	12.75	2.87	0.13				
9	Errol	76.25			20.00	25.69	20.81	8.00	1.75				
	Totals	292.87			123.87	108.31	41.19	15.99	3.38	0.13			
	Per cent	100			42.3	37.0	14.1	5.46	1.1	0.04			
	Errol Area--1/3 controlled												
10	Errol	75.37			27.86	23.56	19.94	3.13	0.88				
11	Aziscohos	154.12			13.87	51.75	64.50	20.62	3.25	0.13			
12	Middle Dam	119.43			46.37	62.62	4.88	3.43	1.63	0.37	0.13		
	Totals	348.92			88.10	137.93	89.32	27.18	5.76	0.50	0.13		
	Per cent	100			25.26	39.5	25.6	7.8	1.65	0.15	0.04		
	Lake Area--controlled												
13	Middle Dam	36.88			11.56	13.13	8.50	2.69	1.00				
14	Upper Dam	127.56			35.68	40.75	38.13	12.37	0.50	0.13			
15	Aziscohos	270.37			3.25	115.49	117.12	31.25	3.01	0.25			
16	Oquossoc	263.81			18.29	107.01	88.88	34.24	13.38	2.01			
	Totals	698.62			68.78	276.38	252.63	80.55	17.89	2.39			
	Per cent	100			9.8	39.6	36.2	11.5	2.6	0.3			
	Drainage-area above Rumford												
	Totals	2073.42		192.37	490.80	674.06	473.65	168.33	51.43	13.27	4.88	3.13	1.50
	Per cent	100		9.28	23.67	32.51	22.84	8.12	2.48	0.64	0.24	0.15	0.07
	Swift River Drainage-Area--uncontrolled												
17	Roxbury	128.26	1.39	23.76	31.29	31.66	30.7	8.23	1.23				
	Per cent	100	1.1	18.5	24.4	24.7	23.9	6.4	1.0				

Data for existing storage-facilities under cooperative control

Owner	Control-point	Lake	Date of dam	Approx. elev. above sea-level	Drainage-area in sq.miles	Surface-area in sq.miles	Storage-capacity, billions cu.ft.	Storage-draft in feet
		Kennebago		1772	103.75	2.74		4.0
O.L. and P.Co.	Dam and station		1917					
U.W.P. Co.	Rangeley Dam	Rangeley	1880	1515	102.62	9.76	1.339	4.0
	Upper dam	{Cupsuptic and Mooselucmeguntic}		1466	383.37	25.95	8.887	12.2
	Middle dam	{Richardson lakes and ponds}		1445	482.87	14.73	5.866	17.5
	Rapid river	Pond-in-River			485.62			
	Crib dam	Parmachenee		1620	105.19	1.33		12.0
Andro.Res.Co.	Aziscohos Dam	Aziscohos	1911	1512	215.75	10.50	9.593	45.0
U.W.P. Co.	Errol Dam	Umbagog	1888	1244	1047.54	15.80	3.245	9.5
I.P. Co.	Pontocook Dam				1217.73	0.55	0.180	12.0
						Total storage	29.110	
	Possible additional storage-facilities other than listed above							
Dart. College	Proposed dam	Diamond streams		1410	154.12	4.30	4.500	86.0

ERIC HINTON (Engineer, International Power and Paper Company of Newfoundland, Ltd., Deer Lake, Newfoundland; communicated)--During the 14-year period of 1926-39, the estimate of runoff at Deer Lake for nine years or two-thirds of the period has been within 10.2 per cent of the actual. The divergence during the other five years was: 12.2, 15.1, 16.9, 26.2, and 28.5 per cent.

[Note--The method used here is quantitative.]

L. STANDISH HALL (Hydraulic Engineer, East Bay Municipal Utility District, Oakland, California) submitted by letter the following discussion on the quantitative method of forecasting stream-flow.

QUANTITATIVE METHOD OF FORECASTING RUNOFF FROM SNOW-SURVEYS

Two methods of forecasting spring runoff from snow-survey data have been in general use. The first has been termed the "percentage-method," and the second the "area-method." The percentage-method was at first popular among forecasters, since it was more readily adapted to the small number of snow-courses available on each watershed when snow-surveys were first initiated several years ago.

The area-method, which has been gradually gaining favor of recent years, requires a greater number of courses. At the same time, several years of record are essential in order to establish quantitative values for watershed-losses during the runoff-period, applicable to various evaporation-rates, vegetation-types, and varying geological formations. Where the data are sufficiently complete to develop these factors accurately, the area-method yields more reliable results.

On the Mokelumne Watershed I have gradually developed a quantitative method, which has yielded quite satisfactory results for the past five years. The method, while termed quantitative, is in a large measure empirical, since the correction-factors are based on the correlation of measured runoff with snow-survey data.

The basic theory of this method is relatively simple and can be briefly stated in terms of the following factors: R = runoff from drainage-area above snow-line during the snow-melt period; W = total water-content of snow on the ground on April 1; P = precipitation on watershed during snow-melt period; E = evaporation- and transpiration-losses from snow-field and from ground-surface. In California the runoff from rainfall on the drainage-area below the snow-line is generally negligible after April 1 and can usually be neglected without error. However, rainfall on the snow-fields is absorbed by the snow, increasing the water-content and prolonging the period of snow-melt runoff. The following relation can be established between the above factors

$$R + E = W + P$$

In order to simplify this relation, it has been assumed that the evaporation-losses from the snow-field and transpiration-losses from the ground-surface bear a relation to precipitation during the snow-melt period. Accepting this assumption, the above equation can be written

$$R/W = 1 + P/W - E/W$$

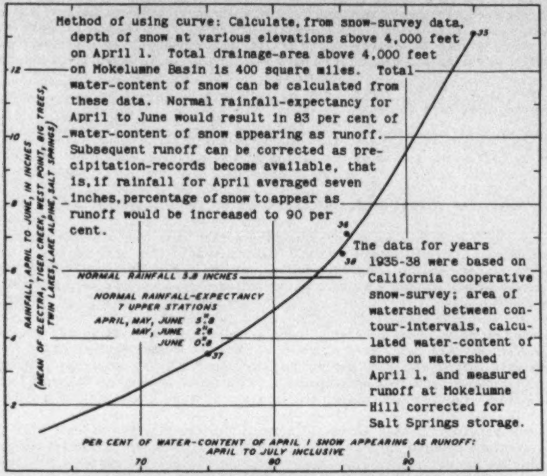
or assuming the last two terms proportional to each other

$$R/W = p$$

This term "p" represents the percentage-relation between the runoff and the water-content of the snow on April 1. The validity of this relationship is open to obvious objections, since it is evident that the evaporation from the snow-field depends to a large extent upon the areal extent of the snow-cover, rather than on the amount of precipitation during the snow-melt period. However, an empirical relationship has been established on the Mokelumne Watershed on the above assumption, which has been relatively consistent.

The method to be described is actually a modification of that developed by the California Cooperative Snow Survey ["Development of snow-surveying in California," by Fred H. Paget, Trans. Amer. Geophys. Union, 1938, p. 686].

On the watersheds of the Sierras and Nevadas in California, I have noted that the snow-line on April 1 may vary between a 4,000-foot and a 6,000-foot elevation above sea-level. When snow-courses were first established, only locations above the 6,000-foot elevation were measured.



Method of using curve: Calculate, from snow-survey data, depth of snow at various elevations above 4,000 feet on April 1. Total drainage-area above 4,000 feet on Mokelumne Basin is 400 square miles. Total water-content of snow can be calculated from these data. Normal rainfall-expectancy for April to June would result in 83 per cent of water-content of snow appearing as runoff. Subsequent runoff can be corrected as precipitation-records become available, that is, if rainfall for April averaged seven inches, percentage of snow to appear as runoff would be increased to 90 per cent.

The data for years 1935-38 were based on California cooperative snow-survey; area of watershed between contour-intervals, calculated water-content of snow on watershed April 1, and measured runoff at Mokelumne Hill corrected for Salt Springs storage.

RAINFALL, APRIL TO JUNE, IN INCHES
(MEAN OF ELECTRA, TIGER CREEK, WEST POINT, BIG TREES, TWIN LAKES, LAKE ALPINE, SALT SPRINGS)
12
10
8
6
4
2
NORMAL RAINFALL 5.8 INCHES
NORMAL RAINFALL-EXPECTANCY
7 UPPER STATIONS
APRIL, MAY, JUNE 5.8"
MAY, JUNE 2.6"
JUNE 0.8"
35
36
37
38
PER CENT OF WATER-CONTENT OF APRIL 1 SNOW APPEARING AS RUNOFF: APRIL TO JULY INCLUSIVE
70
80
90

Fig. 1--Runoff from melting snow at Mokelumne gaging-station, Mokelumne River Basin

With estimates made on the percentage-basis, the zone between 4,000 and 6,000 feet was naturally excluded. It has been found that in two separate years, the snow in the higher altitudes may be essentially the same, but in one year the snow-line on April 1 will end at the 4,000-foot level, whereas in another year with the same snow-conditions at the higher elevations the snow-line will end at the 6,000-foot elevation. When this area is not included in the estimates, a large variation between the forecast and the actual results would naturally result.

In order to correct this deficiency, courses have been established at lower elevations on the Mokelumne Watershed and also on other watersheds in California (see Table 1). As late as 1936 only six stations were officially observed on the Mokelumne Watershed. These were known as:

Station	Elevation	Station	Elevation
Carson Pass	8,600 feet	Lake Alpine	7,500 feet
Blue Lakes	8,000 feet	Silver Lake	7,300 feet
Pacific Valley	7,500 feet	Bear Valley Ridge	6,700 feet

Snow-surveys of these six stations were supplemented by observations made by the East Bay Municipal Utility District of the elevation of the snow-line on April 1.

By 1940, 16 snow-courses were being observed, either in or closely adjacent to the Mokelumne Watershed, which could be used in forecasting spring runoff-conditions.

In California the snow-pack has usually accumulated to its maximum by April 1 so that accurate forecast can be made of the spring runoff. In some years the precipitation in April is sufficiently large as to require a substantial revision of the forecast of April 1 on May 1, and in most years the accuracy of the forecast can be increased by a reestimate made on May 1. The method essentially consists of estimating the runoff based on the snow-surveys of April 1, by correcting the total water-content of snow on the ground by a factor to allow for normal evaporation- and transpiration-losses. This forecast assumes that precipitation-conditions during the remainder of the season will be normal. After the April precipitation-records are available, this forecast can be adjusted by using the actual April precipitation plus a forecast of the May and June precipitation. Since the precipitation in the California mountains after May 1 is generally small, the percentage of error is naturally greatly reduced.

Table 1--California cooperative snow-survey courses, Mokelumne River

Snow-courses	Elevation	Year established
	feet	
Carson Pass	8,600	1930 or earlier
Blue Lakes	8,000	1930 or earlier
Twin Lakes	7,900	1940
Tragedy Springs	7,900	1938
Wheeler Lake	7,800	1937
Pacific Valley	7,500	1930 or earlier
Lake Alpine	7,500	1930 or earlier
Silver Lake	7,300	1930 or earlier
Corral Flat	7,300	1938
Bear Valley Ridge	6,700	1930 or earlier
Lumberyard Station	6,600	1937
Big Meadow	6,500	1940
Cottage Springs	5,700	1938
Ham Station	5,600	1937
Dorrington	4,800	1938
Antelope Springs	4,350	1939

In applying the quantitative method, the drainage-area is subdivided into zones lying between 1,000-foot contour-intervals. The area in each zone is planimetered from United States Geological Survey topographic maps. From the snow-survey on April 1, the mean water-content in inches for each elevation-zone is obtained by averaging the water-content of all snow-courses in each zone. The product of the zone-areas expressed in acres and the average water-content of the snow expressed in feet gives the total water-content of the snow on the ground in acre-feet in each zone. The summation of all zones above the snow-line gives the total water-content of the snow on the Watershed. Table 2 indicates the form of computation for the year 1938.

As previously indicated, this method is not strictly quantitative and necessitates the use of substantially the same number of courses in each year in order to obtain comparable results. The water-content of the snow on missing courses must be estimated, and if many new courses are added to the drainage-area, the factors obtained from the data of the preceding years will require revision in order to make the results applicable to the expanded number of snow-courses.

Table 2--Mokelumne Watershed, estimate of total water-content of snow, April 1, 1938

Contour-interval	Drainage-area	Water-content of snow	Total water-content of snow
feet	sq.mi.	inches	acre-feet
4,000 - 5,000	88	23.5	109,000
5,000 - 6,000	83	33.0	146,000
6,000 - 7,000	63	53.1	178,000
7,000 - 8,000	91	61.0	296,000
8,000 - 10,000	75	54.7	219,000
4,000 - 10,000	400	44.5	948,000

Estimated runoff April 1, 0.83 × 948,000 - 790,000 acre-feet.

Rainfall in April, 4.46 inches; estimated total April to June, 7.26 inches.

Estimated runoff May 1, 0.86 × 948,000 - 815,000 acre-feet.

The percentage of water-content of the snow-pack that will ultimately appear in the stream-channel as runoff depends primarily on the rainfall during the snow-melt period. On the Mokelumne Watershed it has been found, with normal precipitation during the period of melting snow, that 83 per cent of the water-content will run off in the stream-channel during the period between April 1 and July 31.

The percentage of runoff, based on the total water-content in the snow on April 1, can be corrected on May 1 to correspond with the actual April precipitation. The attached graph indicates the relation between the precipitation on the Mokelumne Watershed obtained in April and June and the percentage of the water-content of the April 1 snow appearing as runoff during normal snow-melt period. This graph has been based on the record of four years from 1935 to 1938. It may be subject to further revision as additional data are accumulated. The stations used for the mean precipitation were obtained by comparison with the isohyetel map of the area, which indicated that the average of the seven stations selected closely represent the mean rainfall on the Upper watershed.

In Table 3 a comparison was made of the water-content of the snow on the ground above the 4,000-foot elevation on April 1 with the runoff for the period from April to July, as measured and as estimated from the snow-survey data. It will be noted that for the period 1935 to 1939, Table 3--Comparison of water-content of snow on ground above 4,000-foot elevation on April 1; runoff for April to July, measured and estimated, and mean precipitation on watershed April to June, Mokelumne Watershed

Year	Total water-content of snow, April 1	Runoff, near Mokelumne Hill, April to July, inclusive			Measured run-off as per cent of water-content of snow, April 1	Mean rainfall on watershed	
		Estimated April 1	Estimated May 1	Measured flow		April only	April to June
	acre-feet	acre-feet	acre-feet	acre-feet		inches	inches
1935	584,000	480,000	570,000	556,000	95.2	12.65	13.17
1936	675,000	560,000	560,000	581,000	86.1	2.95	7.10
1937	680,000	560,000	550,000	514,000	75.5	2.46	3.66
1938	948,000	790,000	815,000	821,000	86.6	4.46	6.55
1939	278,000	230,000	205,000	202,000	72.6	0.63	4.11
1940	444,000	400,000[a]	400,000	497,000	111.9	5.93[b]	6.72

[a] 30,000 acre-feet added to estimate for storm of March 29-31, as many courses measured before storm. [b] 4.84 inches of rain March 29-31 included in April record.

the revised estimate on May 1 agrees very closely with the actual measured flow. The results for the year 1940 vary materially from the results in the preceding five years and indicate that the measured flow exceeds the estimate by at least 97,000 acre-feet. The present season has been unique in many respects. The precipitation was somewhat above normal, but warm rains prevented the accumulation of any snow-pack below the 6,000-foot level. As a result, the water-content of the snow above the 7,000-foot level was practically normal, although the total water-content of the snow on the ground above the 4,000-foot level was considerably less than normal. It is probable that the smaller area covered by the snow-field resulted in lower evaporation- and transpiration-losses, and hence a larger percentage of the snow appeared in the stream-channel as runoff. Another factor unfavorable to accurate forecast was the fact that a very heavy storm occurred during the last three days of March and subsequent to the measurement of many of the snow-courses. In the preparation of the estimate of runoff the precipitation during these three days has been included in the April precipitation. Further analysis of the data for the current year, when it becomes available, will undoubtedly result in the determination of factors permitting a more accurate forecast in the future under similar snow-pack conditions.

It is believed that it has been demonstrated that the quantitative method of forecasting runoff from snow-surveys is practical, and future studies will point the way to improving the technique so that accurate results can be obtained over a wide range of climatological conditions.

A QUANTITATIVE FORECAST-SYSTEM OF RUNOFF BASED ON SNOW-SURVEYS AT THE MEAN ELEVATION OF THE SNOW-COVER

John V. Salo

(Presented by J. E. Church)

Foreword

The snow-survey program carried out in the Merrimack River Basin by the Public Service Company of New Hampshire was only first started in 1938 with the cooperation of the United States Weather Bureau. This original program has been continued and expanded during 1939 and 1940. Prior to 1938 no snow-survey field-work and no runoff-analyses had been attempted in the Merrimack Area, so, as a result, no previous records were available for purposes of comparison. Therefore, the data obtained from our limited experience, particularly the surveys in 1939, serve as the basis for this report.

A review of this experience has brought out two important factors which are characteristic of the Merrimack Area, and which are probably different from those met with in the west. First, the spring runoff in the Merrimack Area is usually the result of a combination of snow-melt and heavy rainfall. It is entirely possible at any time in the spring to be confronted with weather-conditions which can cause disastrous floods in this Area. Second, runoff due to snow-melt or rainfall can occur in certain portions of the Area simultaneously with continued build-up of snow-cover in other portions.

These two factors have influenced and shaped our methods of survey and calculation. It is good insurance to maintain a close check on the snow-cover as it builds up and then depletes until we are certain that the safe runoff-period is reached. It also is imperative that we know at frequent intervals to a considerable extent the amount of potential water-supply available in the snow-cover and the distribution of this water-content over the entire area.

These needs first became evident during the progress of the 1939 snow-surveys conducted in the headwaters of the Merrimack River. The problem of the frequency of surveys was easily dealt with. For the problem of determining the amount of potential water-supply and its distribution over the entire area surveyed, we had recourse only to our limited data. At that time, it appeared extremely appropriate to devise and utilize a method of calculation because of the approach of the period of possible sudden and extreme runoff.

This definite need of a simple "measuring stick" which would express the potential water-supply available in large snow-covers, brought about the development of the "mean-elevation" method of attack. Sheer necessity demanded that the snow-survey data gathered from representative courses in the Merrimack River Drainage-Area be translated into useful information. The "mean-elevation" method interprets the significance of these snow-survey data. It provides a basis for determining potential water-supply existent in snow-covers of large areas by its interpretation of the data from the representative courses within those areas.

Upon the analysis of the 1938 and 1939 data, the "mean-elevation" method of attack was formulated. Briefly, the calculations made by utilizing this method follow two general principles. First, it has been possible to construct a curve for each complete survey, which illustrates the general relation between water-content and elevation for the entire area as a unit. Second, in order to properly weight the data obtained from representative snow-courses in a given individual area, which is a part of the whole unit, we have tried to determine the water-content at the average or "mean-elevation" of that component area. This was accomplished by projecting this "mean-elevation" on to the "water-content-elevation" curve which was constructed in step one. These two principles are outlined in more detail in the body of this report.

By the use of this "mean-elevation" method, it has been possible to make complete calculations for each of the 1939 snow-surveys. This trend has been tabulated in detail in the original report. It will serve as a basis for future comparison and also will be used as a source for future analysis of runoff in an endeavor to determine the correlation between snow-cover and runoff.

The body of this report will illustrate the work carried out up to this time.

Method of survey

Further explanation should be made of the frequency of surveys that we carry out, which is perhaps different from those conducted in the west. Our first complete survey is made in the middle of January and successive surveys are made in intervals of approximately two weeks, depending upon weather-conditions. These surveys are continued through the runoff-period. This runoff usually is very noticeable by at least the middle of April, and we are able to follow its progress until the snow-cover is practically depleted.

Because of the changeability of New England weather, it is reasonable to expect a partial runoff early in the spring season, followed by additional increases in snow-cover. In some instances an expected partial runoff has turned into steady and rapid runoff because of changing weather-conditions. As a matter of record, the Merrimack Basin has experienced its severest flood-stages during spring runoff when heavy rainfall has been superimposed upon the snow-melt.

For reasons of this nature, it seems advisable to keep a check on our snow-cover until we feel certain that the steady runoff-period has safely begun.

Description of areas

The total drainage-area of the Merrimack River above Manchester at the junction of the Piscataquog and Merrimack rivers, as illustrated in Figure 1, represents 3,059 square miles. This basin is made up in the greater part of four major tributaries. These are the Pemigewasset and Winnepesaukee areas in the north, and the Contoocook and Piscataquog areas in the south. Included in the two major northern areas are three large bodies of water, namely, the Winnepesaukee, Newfound, and Squam lakes. On these tributaries and on the Merrimack River are a total of 15 hydro-generating plants.

The northern areas are made up of steep slopes and the tributaries empty directly into the main stream. The topography is ideal for rapid runoff. The maximum elevation for the entire area is located in the northern basins at 5,250 feet. The two southern sections are not quite as steep in the headwaters and flatten out quickly. These tributaries wander about considerably before they join the main stream.

The areas in which the snow-survey field-work of 1939 was carried out are the two principal northern basins. These are illustrated in Figure 2. They are the Pemigewasset River Area above Bristol, and the total Winnepesaukee Area above its junction with the Pemigewasset River at Franklin. These two combined areas represent 1,335 square miles of drainage.

This illustration also shows the permanent location of our 16 survey-stations which were sampled in 1939. They range from a maximum elevation of 4,000 feet to a minimum of 600 feet. These two major areas have been subdivided into 20 component areas, representing the drainage-areas above Government gaging-stations, above hydro stations, and for tributaries or lakes as complete units. The reason for such subdivision is to simplify the calculation of the potential runoff and to provide a means of comparison between component areas and because of our ability to measure actual runoff at these points.

Some of the survey-stations are located on the height of land between two adjoining areas. In such a manner it is possible to use those data to serve for both areas. In general, most areas include two survey-stations--one at a high elevation and one at a lower elevation in the Valley. In this way it is possible to obtain comparative data for these individual areas, which is utilized by the "mean-elevation" method.

The expanded 1940 basis of our snow-survey program is illustrated by Figure 2X. This illustration again pictures the total drainage-area of the Merrimack River above Manchester of 3,059 square miles.

In addition to the 16 permanent survey-stations established in 1939, 12 more have been included in the present snow-survey program. Eleven of these stations have been established in the Contoocook River Drainage-Area. These courses range from 900 feet to 1,800 feet in elevation within this particular area, which embraces a variation in elevation from a maximum of 3,165 feet to a minimum of 250 feet.

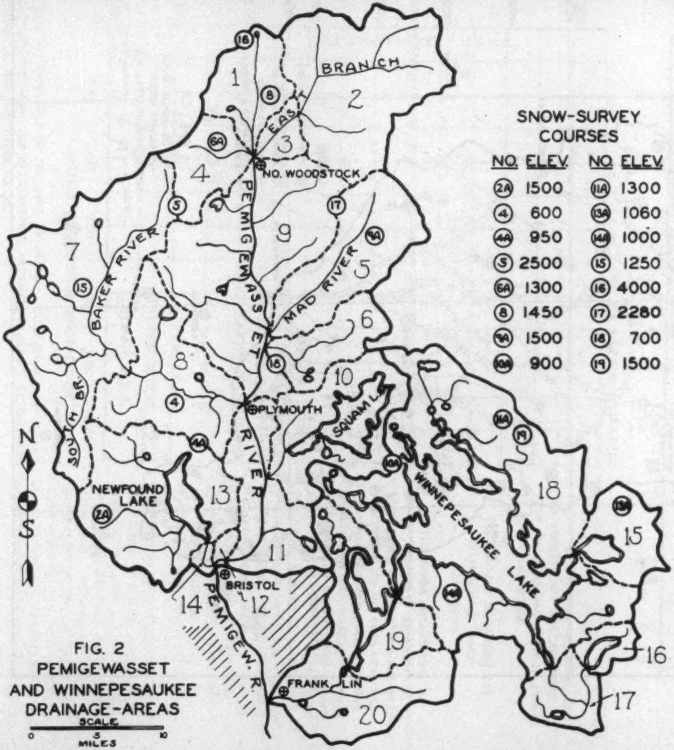
Also shown in Figure 2X are the locations of 39 precipitation-stations, within and adjacent to the total drainage-area. Four separate agencies maintain precipitation-stations and their records are available for investigation. These records will serve a twofold purpose. First, they will provide a source for data which can be utilized to make adjustments in the event that snow-survey field-work is interrupted by storms of any magnitude. As our program now requires five successive days for each field-trip, it is essential that we have recourse to a means with which we can adjust all field-work data to a common basis in the event of such storms. Second, data from these precipitation-stations will be useful during the runoff-period. These data will aid in the determination of the individual contribution of rainfall and snow-melt in producing the spring runoff. Both of these procedures require the construction of contours of water-content for the storms under consideration. These methods will be treated in more detail in the conclusions.

Weighting of snow-survey data at the "mean elevation"

An examination of the snow-survey data available during the progress of the 1939 field-work revealed the fact that we had no satisfactory method of weighting these data properly. It did not seem logical to calculate arithmetical averages of water-content for individual areas. Such averages would not provide accurate comparisons between individual areas due to the divergence of snow-course elevations. These averages could not serve as a source for accurate calculations of potential water-supply in those areas.

With this idea in mind, it seemed advisable to examine the variation of elevation in each component area and thereby determine the relative position of the snow-course elevations in each area. A method which attempts to take into consideration this relation of elevation was devised. The best approach at this early stage of our snow-survey experience has been to determine the "mean elevation" in each area and to consider that arbitrary elevation as more nearly representative of average water-content in the snow-cover for that area.

Because of our relatively short snow-survey experience, we have not as yet been able to test this supposition with actual field-work data. However, we have tried to make comparisons with


BRANCH
EAST
NO. WOODSTOCK
PEMIGEWASSET
MAD RIVER
BAKER RIVER
SOUTH BR.
PLYMOUTH
RIVER
SQUAM L.
WINNEPESAUKEE LAKE
NEWFOUND LAKE
BRISTOL
PEMIGEW. R.
FRANKLIN
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
N
S

SNOW-SURVEY COURSES

NO.	ELEV.	NO.	ELEV.
(2A)	1500	(11A)	1300
④	600	(13A)	1060
(4A)	950	(14A)	1000
⑤	2500	⑮	1250
(6A)	1300	⑯	4000
⑧	1450	⑰	2280
(9A)	1500	⑱	700
(10A)	900	⑲	1500

FIG. 2
PEMIGEWASSET
AND WINNEPESAUKEE
DRAINAGE-AREAS

SCALE
0 5 10
MILES

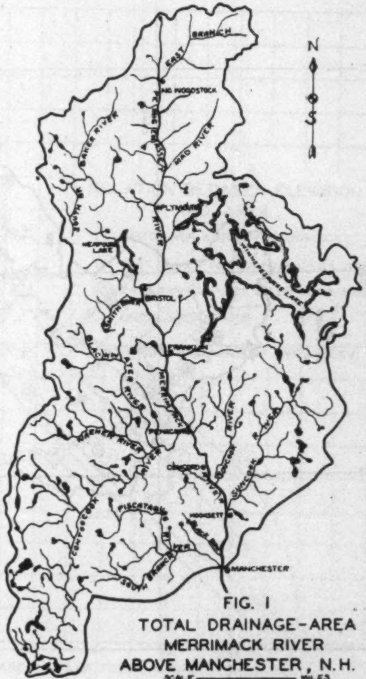

EAST BRANCH
NO. WOODSTOCK
PEMIGEWASSET
MAD RIVER
BAKER RIVER
PLYMOUTH
RIVER
NEWFOUND LAKE
BRISTOL
WINNEPESAUKEE LAKE
FRANKLIN
MERRIMACK
BLACKWATER RIVER
WARNER RIVER
CONTOOCOOK
CONCORD
SOUCOOK RIVER
SUNCOOK R.
PISCATAQUOG RIVER
HOOKSETT
SOUTH BRANCH
MANCHESTER
N
S

FIG. 1
TOTAL DRAINAGE-AREA
MERRIMACK RIVER
ABOVE MANCHESTER, N.H.

SCALE 0 5 10 15 MILES

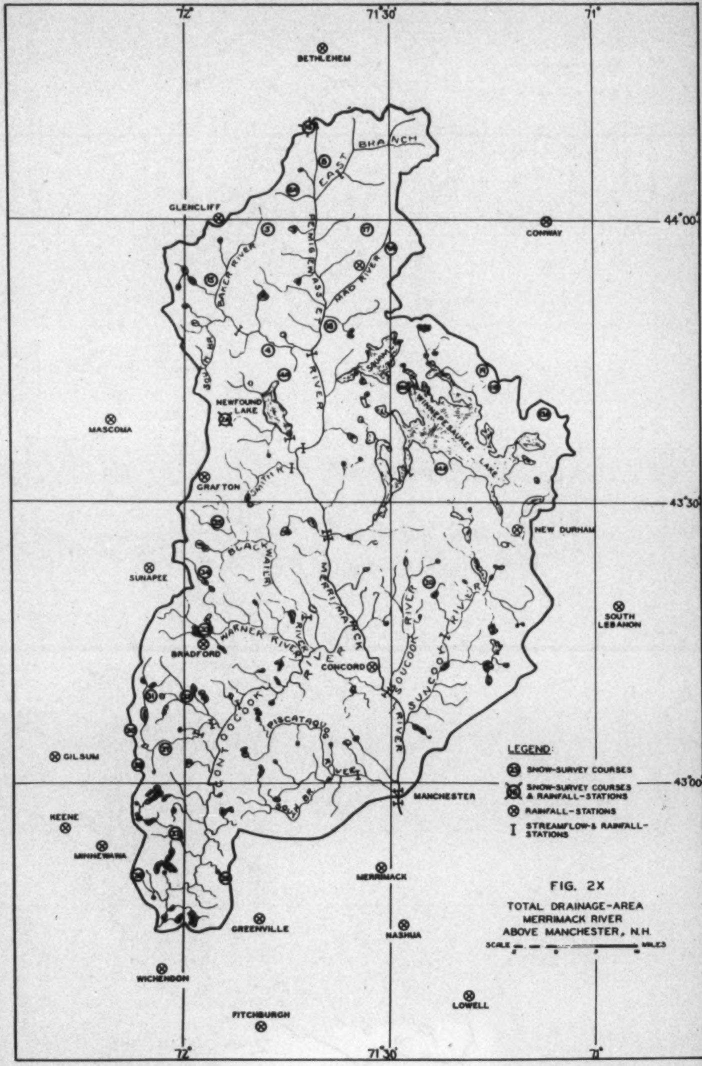

72°
71°30'
71°
44°00'
43°30'
43°00'
BETHLEHEM
EAST BRANCH
GLENCLIFF
CONWAY
PEMIGEWASSET RIVER
MAD RIVER
BAKER RIVER
SOUTH BR.
NEWFOUND LAKE
MASCOMA
SMITH R.
GRAFTON
WINNIPESAUKEE LAKE
NEW DURHAM
BLACKWATER
SUNAPEE
MERRIMACK RIVER
SOUCOOK RIVER
SUNCOOK RIVER
SOUTH LEBANON
WARNER RIVER
BRADFORD
CONCORD
CONTOOCOOK RIVER
PISCATAQUOG RIVER
SOUTH BR.
GILSUM
MANCHESTER
KEENE
MINNEWAWA
MERRIMACK
GREENVILLE
NASHUA
WICHENDON
FITCHBURGH
LOWELL
LEGEND:
SNOW-SURVEY COURSES
SNOW-SURVEY COURSES & RAINFALL-STATIONS
RAINFALL-STATIONS
STREAMFLOW- & RAINFALL-STATIONS
SCALE
MILES

FIG. 2X

TOTAL DRAINAGE-AREA
MERRIMACK RIVER
ABOVE MANCHESTER, N.H.

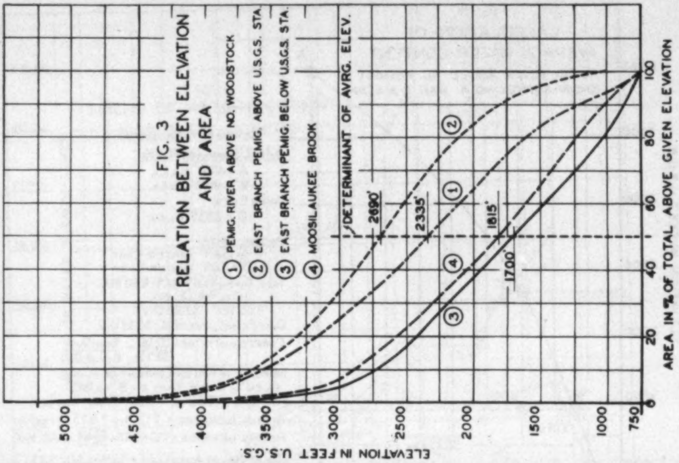


FIG. 3
RELATION BETWEEN ELEVATION AND AREA

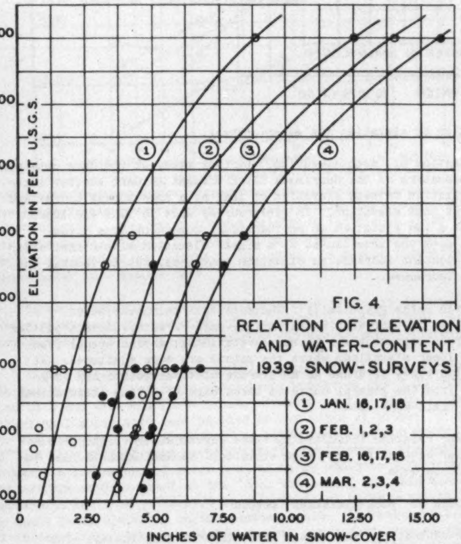


FIG. 4
RELATION OF ELEVATION AND WATER-CONTENT 1939 SNOW-SURVEYS

more rigorous zone-methods, and the results are satisfactory. This is discussed in more detail in the conclusions.

Explanation of method for determining "mean-elevation"

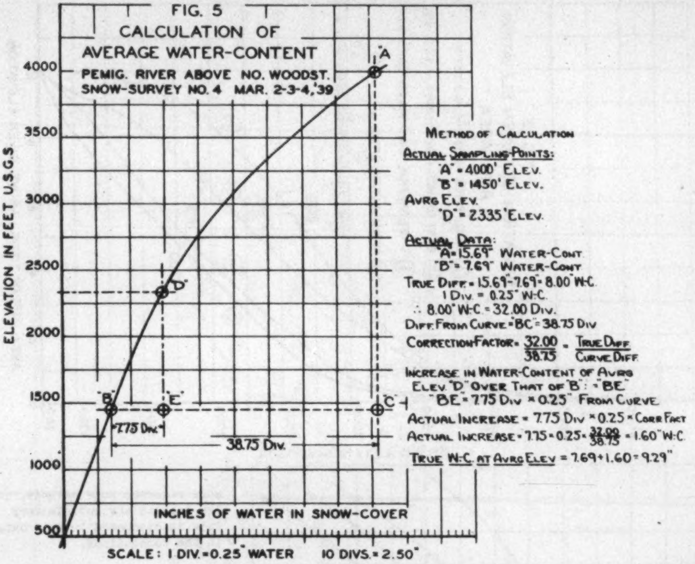
The areas considered, as shown previously in Figure 2, total 20. The maximum and minimum elevation of each area was recorded and the area then was subdivided into component areas representing differences in contours of 500 feet in elevation. The total component above each elevation was carefully measured by planimeter. These data were then converted into per cent of total area. The quickest way in which to determine average or "mean elevation" from these figures is the graphical method.

Curves were drawn for each individual drainage-area showing the per cent of total area above each 500-foot interval of elevation. Average or "mean-elevation" exists at that elevation where 50 per cent of the area is above and 50 per cent is below. This procedure was used for all areas. It is as accurate as and quicker than any arithmetical method. Figure 3 illustrates this procedure with four typical areas of the Merrimack Basin.

FIG. 5

CALCULATION OF AVERAGE WATER-CONTENT

PEMIG. RIVER ABOVE NO. WOODST.
SNOW-SURVEY NO. 4 MAR. 2-3-4, '39



METHOD OF CALCULATION

ACTUAL SAMPLING-POINTS:
"A" = 4000' ELEV.
"B" = 1450' ELEV.
AVRG ELEV.
"D" = 2335' ELEV.

ACTUAL DATA:
"A" = 15.69" WATER-CONT.
"B" = 7.69" WATER-CONT.
TRUE DIFF. = 15.69" − 7.69" = 8.00" W-C.
1 DIV. = 0.25" W-C.
∴ 8.00" W-C. = 32.00 DIV.
DIFF. FROM CURVE = "BC" = 38.75 DIV
CORRECTION FACTOR = $\frac{32.00}{38.75} = \frac{\text{TRUE DIFF}}{\text{CURVE DIFF}}$
INCREASE IN WATER-CONTENT OF AVRG ELEV. "D" OVER THAT OF "B" : = "BE"
"BE" = 7.75 DIV × 0.25" FROM CURVE
ACTUAL INCREASE = 7.75 DIV × 0.25 × CORR FACT
ACTUAL INCREASE = $7.75 \times 0.25 \times \frac{32.00}{38.75} = 1.60$" W-C
TRUE W-C. AT AVRG ELEV = 7.69 + 1.60 = 9.29"

The relation of elevation and water-content

In conjunction with the determination of "mean elevation," further study of the data obtained from the survey-experience in the headwaters of the Merrimack River brought forward another interesting fact. This is the apparent relation between elevation of land at a snow-survey course and the water-content of the snow-cover at that elevation. In every survey made in 1939 and 1940, the data reveal that a snow-course at a low elevation in an individual component area gives smaller values of water-content than does the snow-course at a higher elevation within that same component area. Not only does water-content increase as elevation increases, but in general the rate of change in water-content also increases.

It is possible to construct curves which graphically illustrate this characteristic. Figure 4 pictures the first four surveys of 1939 with actual survey-data of water-content plotted against elevation. These general curves represent all 16 survey-stations. A discrepancy from this general curve does exist at the lower elevations where the points are more scattered. At these lower elevations this constructed curve is drawn as an average of these points and is practically linear. The discrepancy from the general curve is taken care of in the calculations by an adjustment based on the actual field-work data.

Because of the apparent non-linear relation indicated by these curves at the higher elevations, the logical calculation of water-content at the "mean elevation" necessitates the use of these curves. That is actually how it is done.

Application of "mean-elevation" method

The computation of average water-content for individual areas is done graphically. The actual data obtained from the field-work are utilized. The two main factors in which we are interested are elevation and the slope of the water-content curve plotted against these elevations. Such a curve has been drawn to scale for snow-survey No. 4, and is illustrated in Figure 5. This curve has been moved over to the zero-axis of water-content and this reference-

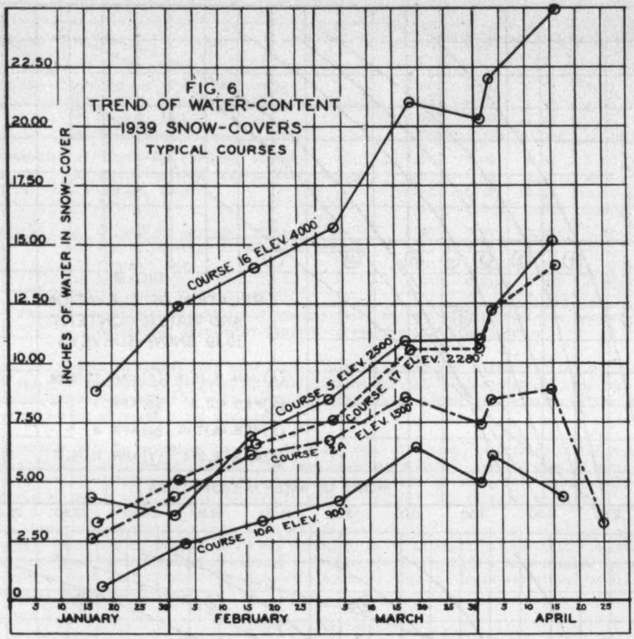


FIG. 6
TREND OF WATER-CONTENT
1939 SNOW-COVERS
TYPICAL COURSES

line has not been numbered other than to indicate the scale. The scale is ten divisions = 2.50 inches of water. The water-content points of individual areas in some cases may deviate somewhat from this curve. This difference can be explained by the fact that it is an average curve representing the data of all points in all areas. A simple correction is made which will be illustrated later in a sample case.

Three variations of the basic attack are necessary in order to take care of the three different cases that are computed. These cases are as follows: (1) Eight areas include two or more survey-points; (2) three areas include one survey-point; (3) nine areas have no survey-points.

Figure 5 illustrates the attack for an area with two survey-points. From the field-work data the Pemigewasset River Basin above North Woodstock has 7.69 inches of water-content at an elevation of 1,450 feet and 15.69 inches of water-content at an elevation of 4,000 feet. These two elevation-figures have been plotted on the curve at points "B" and "A", respectively. The line for the computed "mean elevation" of 2,335 feet has been drawn to intersect the curve at point "D" and then dropped down perpendicularly to intersect the base-line at point "E". Line "BE" represents the amount of water-content to be added to 7.69 inches at point "B", in order to give the average water-content at the "mean elevation" for this area. Actually, line "BC", which represents the true difference in water-content between points "B" and "A" of 8.00 inches, should be equal to 32 divisions on the plotted scale. By measurement on this curve it is equal to 38.75 divisions because of the probable general curve-deviation already explained. In order to apply the proper correction-factor to the 7.75 divisions representing water-content "BE", it is necessary to multiply this increase in water-content by the ratio of (32/38.75). Thus the true increase of water-content for the average elevation over point "B" is equal to (32/38.75) × 0.25 inch × 7.75 divisions. The gain in water-content from this product = 1.60 inches. Therefore, the average water-content is equal to 7.69 inches plus 1.60 inches = 9.29 inches. This figure

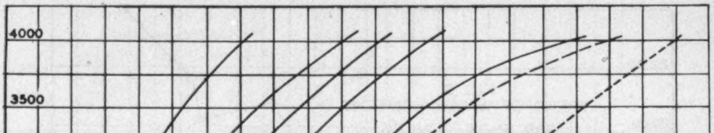


FIG. 7
RELATION OF ELEVATION
AND WATER-CONTENT
1939 SNOW-SURVEYS

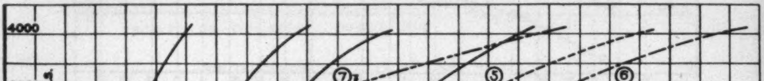


FIG. 7X
RELATION OF ELEVATION
AND WATER-CONTENT
1940 SNOW-SURVEYS

is the true water-content for the "mean elevation" in this area. This same procedure has been used in determining average water-content for all other areas with two or more survey-points.

In cases of areas with but one survey-point, fundamentally the same approach is used. The single point is plotted on the curve as a base-line. The line of "mean elevation" is drawn as

Total area	Item	1939 snow-surveys, station No.				
		4	5	6B	6A	7
Above Bristol ㉑	(a) Calculated average, inches	6.26	8.61	7.75	8.85	9.28
	(b) Approx. average at 1,390 feet, inches	5.88	8.08	7.00	8.00	8.38
	(c) Change, inch	-0.38	-0.53	-0.75	-0.85	-0.90
	(d) Ratio (b/a)	0.940	0.938	0.903	0.905	0.903
Above Franklin Falls Junction ㉒	(a) Calculated average, inches	3.87	6.00	4.52	5.63	3.21
	(b) Approx. average at 710 feet, inches	4.63	6.45	4.63	5.75	4.23
	(c) Change, inch	+0.76	+0.45	+0.11	+0.12	+1.02
	(d) Ratio (b/a)	1.197	1.073	1.025	1.020	1.320
For combined areas ㉓	(a) Calculated average, inches	5.40	7.67	6.58	7.67	7.06
	(b) Approx. average at 965 feet, inches	5.10	7.05	5.51	6.55	5.75
	(c) Change, inch	-0.30	-0.62	-1.07	-1.12	-1.31
	(d) Ratio (b/a)	0.945	0.919	0.837	0.854	0.815

Fig. 8--Comparison of calculated average water-content with approximate average determined from water-content curves for 1939 snow-surveys

before and dropped to intersect this base-line. In this instance no correction-factor is necessary and the true increase or decrease in water-content for the "mean elevation" from that of the survey-point can be determined by multiplying the intersected number of divisions by the scale-figure of 0.25 inch of water = one division.

For an area with no survey-points, its line of "mean elevation" is dropped to the base-line of an adjacent area having approximately the same "mean elevation." The increase in water-content is computed over the minimum survey-figure for this adjacent area, taking into consideration the same correction-factor as explained before, if such exists for this adjacent area.

This complete method for determining potential water-supply in snow-covers of drainage-areas is reasonably rapid and appears to be fairly accurate, as it attempts to take into consideration the effect of "mean elevation." Future data will undoubtedly indicate a more precise method and will provide us with sufficient information with which to test the "mean-elevation" method. For the present it may prove useful.

General discussion

The build up and depletion of snow-covers at typical survey-stations is illustrated in Figure 6. These trends provide their most useful information when the runoff-period has started. They supply the basic data necessary to substantiate the discussion of the extent of snow-melt and runoff. By the comparison of the trends of all 16 survey-stations, it is possible to determine the progress of the limits of runoff.

It is interesting also to point out the steeper slope of water-content trends during the build-up period for the survey-points at the higher elevations than at points at the lower elevations. This fact refers directly back to the original contention that water-content-elevation curves in this area tend to assume shapes that are more convex than linear, particularly at the higher elevations.

The trend of water-content for the entire 1,335 square miles sampled is best shown by the curves of Figures 7 and 7X. These curves summarize all of the complete surveys made in 1939 and 1940. They have served as the basis for the determination of potential water-supply in the entire snow-cover for each survey by use of the "mean-elevation" method. The 1939 calculations have been tabulated in detail. This resulting table is able to show the quantitative progress of potential water-supply from one survey to the next for individual component drainage-areas, and subsequently for any combination of these areas representing the drainage above a given location.

This information will be useful in our prospective study to determine the correlation between actual and potential runoff.

Conclusions

The use of the "mean-elevation" method has provided us with the quantitative "measuring stick" which we needed at this time. It offers a fairly rapid way with which to make potential water-supply calculations. As soon as the water-content-elevation curve has been established, the calculation for each individual area is a repetition of a simple process. At present it appears reliable, for it makes use of the actual field-work data and all adjustments are made from that basis. Future field-work will supply additional data with which we can make comparisons to test the exact accuracy of the "mean-elevation" method of attack.

By utilizing the "mean-elevation" method the following requirements have been fulfilled:

(1) It is possible to calculate potential water-supply of snow-covers when no previous records are available.

(2) It provides a means for estimating potential water-supply in adjacent component areas in which it has been impossible to establish snow-survey courses.

(3) It provides a means for making comparisons between component areas on the same basis.

(4) It establishes a means for following the trend of build up and depletion of snow-covers in component areas.

(5) It provides a means for calculating potential water-supply existent above any major location on the Merrimack River or its tributaries.

Comparisons have been made of the 1939 surveys to check its reliability by using the only means available at present. This was accomplished by dividing snow-covers into zones of water-content and then determining averages from these zones. Calculations were made on the basis of two zones for actual typical areas with two survey-points, and also on the basis of zones representing intervals of 500 feet of elevation for both typical and assumed cases.

The cases with two zones made use of actual field-data and the cases with zones at intervals of 500 feet of elevation made use of the general water-content-elevation curves. The average water-content figures derived for actual typical areas were one-half per cent to four per cent higher than those obtained by the "mean-elevation" method. The results derived for assumed general cases varied from two per cent to ten per cent higher than those computed by the "mean-elevation" method for these same assumed cases. In all instances the zone-method gave higher average water-content figures than the "mean-elevation" method.

We appreciate the fact that these figures do not actually test the "mean-elevation" method. We plan to determine the actual runoff produced by the 1939 snow-cover by an analysis of our stream-flow records. A comparison on this basis will be more of an acid test. As we accumulate more records at our established survey-stations in the future, we shall be in a better position to compare the new survey-data with previous records. We will then be able to make proper modifications to the "mean-elevation" method and determine its relation to the comparison of records from year to year.

As a final word, for purposes of comparison we have determined average water-content by an approximate method for the Pemigewasset and Winnepesaukee basins as a whole. (See Table 1.) By utilizing the water-content-elevation curve and the "mean-elevation" for each major basin, it is possible to obtain a figure of average water-content. The comparison between these approximate values and those computed by the more exact "mean-elevation" method is illustrated in Figure 8 for the 1939 surveys.

Inspection shows that for all five surveys considered, the approximate averages are less for the Pemigewasset and Combined basins and are greater for the Winnepesaukee Basin than the calculated averages. The ratio of approximate average to calculated average for the Pemigewasset Basin varies from six per cent to 9.7 per cent from unity. The ratio for the Winnepesaukee Basin shows the maximum deviation by varying from two per cent to 32 per cent from unity. An intermediate variation is shown by the combined areas of ratio-divergence of 4.6 per cent to 18.5 per cent from unity.

These percentages indicate the limits of error which would have been incurred if the approximate method had been utilized at any time for the 1939 surveys. Future data may or may not supplement these limits and make available some general rule for adjusting approximate values to approach those derived by calculation.

A final reference is made again to the importance of the precipitation-stations in Figure 2X during the spring season. For our contemplated runoff-study, the data obtained from these stations will be invaluable.

During the spring runoff-season, the changes in snow-cover represent only a part of the total runoff. In order to determine the actual grand total of runoff which occurs in the interval

Table 1--Snow-survey data, 1939 and 1940, Pemigewasset and Winnepesaukee areas

No.	Name of point	Elevation, feet	Water-content of snow-cover in inches														
			1939 Survey								1940 Survey						
			No.1 Jan. 16,17,18	No.2 Feb. 1,2,3	No.3 Feb. 16,17,18	No.4 Mar. 2,3,4	No.5 Mar. 17,18,19	No.6B Apr. 1	No.6A Apr. 3	No.7 Apr. 15,16,17	No.1 Jan. 29,30,31	No.2 Feb. 21,22,23	No.3 Mar. 11,12,13	No.4 Mar. 25,26,27	No.5 Apr. 8,9,10	No.6 Apr. 22,23 24,25	No.7 May 7,8,9
2A	Cardigan Mt.	1,500	2.67	4.38	6.23	6.73	8.54	7.43	8.46	8.85	4.35	7.15	9.71	12.58	10.13	10.34	0.45
4	Polar Caves	600	2.00	3.23	3.69	4.60	7.22	6.02	7.03	4.89	2.35	4.50	5.65	7.42	3.98	0.75	0.00
4A	Hoyt Hill	950	2.00	3.83	5.42	5.90	7.89	6.45	7.37	6.94	3.29	5.85	7.35	10.06	6.69	3.35	0.00
5	Breezy Point	2,500	4.30	3.58	6.93	8.38	10.89	11.04	12.14	15.08	4.21	6.60	8.67	12.15	12.29	12.98	3.58
6A	Lost River	1,300	2.96	2.73	5.16	5.71	6.91	5.20	6.30	7.33	2.50	4.54	6.21	8.02	6.73	5.21	0.00
8	Flume	1,450	3.00	4.75	6.52	7.69	9.84	10.22	11.52	13.40	3.13	5.13	7.38	9.88	10.23	9.88	0.00
9A	Waterville Valley	1,500	1.67	4.29	4.63	5.64	8.47	7.35	8.60	9.33	3.69	6.98	8.58	11.16	8.98	6.75	0.00
10A	Center Harbor	900	0.58	2.46	3.27	4.17	6.44	4.95	6.07	4.35	2.15	4.58	5.73	7.50	5.98	5.79	0.00
11A	Ossipee Park	1,300	0.50	4.17	4.56	5.08	6.31	4.73	6.05	3.71	....	....	....	....	....	....	....
11B	Bald Knob	700	....	....	....	....	....	....	....	....	1.60	4.35	5.19	6.81	2.02	0.00	0.00
13A	North Wolfeboro	1,060	0.71	3.73	4.38	4.88	7.27	5.93	7.25	7.35	2.58	6.08	8.48	10.58	7.00	6.29	0.00
14A	Gilford	1,000	0.38	3.96	4.33	4.83	6.75	5.57	6.89	6.35	2.67	5.65	7.42	9.08	5.25	3.41	0.00
15	Wentworth	1,250	2.80	3.50	4.14	4.61	7.06	6.52	7.62	5.79	2.38	4.48	6.27	7.58	4.88	1.90	0.00
16	Cannon Mt.	4,000	8.80	12.46	13.95	15.69	21.00	20.20	21.91	24.97	7.35	11.90	15.35	21.23	25.90	29.02	21.88
17	Thornton Gap	2,280	3.25	5.08	6.59	7.58	10.58	10.58	12.08	14.10	3.81	7.27	8.77	11.15	10.02	10.90	2.65
18	Campton Hollow	700	0.94	2.83	3.69	4.81	6.80	4.54	5.46	3.10	2.31	4.54	5.98	7.48	3.73	0.00	0.00
19	Plante Estate	1,500	1.40	5.15	5.65	6.21	8.37	6.51	7.83	4.46	2.13	5.25	8.06	10.27	6.73	5.93	0.00
20	Loudon Center	820	....	....	....	....	....	....	....	....	....	....	6.00	7.40	2.50	0.00	0.00

of time between surveys, it is also necessary to take into account the form and total amount of precipitation which has fallen during that interval of time.

This necessitates the construction of contours of water-content for the storms occurring during that runoff-interval between surveys. In this manner it is possible to adjust the data to represent the maximum condition of 100 per cent water-retention by the snow-cover. This is accomplished by a summation of contour-determined values to those of the previous survey, for all snow-survey stations.

Then the difference calculated between these maximum values and those of the following survey will represent the grand total runoff for that interval. The actual calculations for the 100 per cent condition can be accomplished by the "mean-elevation" method.

That is what we propose to do for our 1939 and 1940 snow-survey runoff-studies.

Public Service Company of New Hampshire,
Manchester, New Hampshire

DISCUSSION

JOHN V. SALO (communicated)--We had originally planned to incorporate runoff-studies in the report in order to tell a more complete story. We have walked into two problems, instead. The first of these, the evaluation of the contribution of rainfall during the runoff-period, we feel that we can handle satisfactorily. This involves digging into the precipitation-records of three other agencies and assembling sufficient data to be tackled in a fashion as outlined in the report.

The second problem is more troublesome. We have discovered that our pondage-charts for three major reservoirs are in error. I feel that these should be corrected first in order to know for certain that at least part of our prospective work is sound. This will be accomplished in due time.

We hope to dispose of these problems during the summer of 1940. By then we should be in a better position to correlate these studies.

H. P. BOARDMAN (Chairman, Nevada Cooperative Snow-Surveys, Reno, Nevada)--The paper by Mr. Salo is very interesting and gives evidence of much work, both in field snow-surveys and in the analysis of results. The frequent surveys at approximately two-week intervals are valuable in showing the building up of the snow-blanket water-content and later depletion by melting, thus enabling progress-estimates to be made of possible flood-producing water-supply.

Nothing is said as to whether storage is developed in any of the lakes by outlet control so that the snow-surveys could be applied to forecasting supply for power-development or other uses. Also no mention seems to be made of the assumed ratio of runoff to water-content in estimating possible flood-danger.

As to the mean-elevation method of determining the average water-content for a given area, the author states that the zone-method always gives higher water-content average than does the mean-elevation method. The graphs appear to show that this must be the case and I would think that the first natural assumption or trial elevation for a mean water-content should have been that elevation at which 55 per cent or 60 per cent of the area lies below and 45 per cent or 40 per cent above it, rather than the 50 per cent elevation. However, the check appears to show that the difference in resulting average water-content determination between the two methods is not large enough to be serious.

Possibly the apparent difference in behavior of the Winnepesaukee Basin from the other basins may be in part due to the large percentage of water-surface area at practically a constant elevation.

[For addendum to this paper with illustrations of the difficulties of snow-surveying, see pp. 992-995, copy for which was received too late to be included with the above article.]

SOIL-MOISTURE STUDIES AS AN AID IN FORECASTING RUNOFF FROM SNOW-COVER

George D. Clyde

It has long been recognized that runoff is a residual and equals the difference between the total precipitation on, and the losses from, a given watershed. The runoff need not be directly from the precipitation. Most of the runoff occurs over the surface or through the earth-mantle. That which occurs through the earth-mantle may be considerably delayed in transit and opportunities for losses may be much greater.

Forecasting water-supplies for a specific purpose requires a limitation in time of occurrence of runoff. The yield of a stream must be usable at the time of the occurrence of flow. The presence of artificial or natural reservoirs affects the usable yield insofar as they control the flow and make it available at the time it is needed. The lag in stream-flow caused by a delayed movement of water through the ground may be so great as to cause the runoff to miss the peak-demand for water, and the losses due to evaporation, transpiration, and watershed-leakage while in transit through the ground may be as a result much larger. Such losses reduce the effective yield. Forecasts of runoff based upon snow-cover must therefore take into consideration the soil-moisture conditions before the precipitation begins to accumulate on the watershed in the form of snow and during the period when the water in snow-storage is released to feed the surface-streams and ground-water supplies.

Field-capacity of a soil is defined as the amount of moisture it will hold against the pull of gravity. This capacity varies widely with different soils. Regardless of the type of soil, if the moisture present is less than the field-capacity, this deficiency will be made up by water penetrating into the soil from melting snows and will be held in the soil against the pull of gravity. This water is not available to make stream-flow farther down the watershed and at a later date. It is lost to stream-flow and is usually consumed by growing plants or evaporation.

Many factors affect the rate of absorption by the soil or the rate of percolation into it. Much has been written in technical journals during the past ten years as to the effect of absorption on the yield of a watershed. Most of these contributions to the literature have had to do with precipitation which falls as rain. Little has been done to determine the amount of water from a given snow-cover which is required to bring the moisture in the earth-mantle under the snow-cover up to field-capacity and to hold it there during the melting season.

If the moisture in the earth-mantle is held at field-capacity and no transpiration- or evaporation-losses occur, all additional water absorbed from the snow-cover will pass on through the mantle and join the ground-water which is an important source of streams. Such evaporation- and transpiration-losses as do occur from the earth-mantle must be replaced by water from the melting snow in order to maintain the soil-moisture at field-capacity.

The depth and nature of the earth-mantle varies widely on each watershed. It is extremely difficult therefore to determine quantitatively the amount of water necessary to prime the soil on a given watershed. Furthermore, the rate of melting and the condition of the surface of the earth-mantle will determine to a large extent the amount of water from the melting snow that gets into the soil to prime the earth-mantle. For example: An earth-mantle which is frozen before the snow begins to accumulate will absorb very little water from the melting snow if the frozen condition continues during the melting season. Further, if the melting is so rapid that it saturates the surface of the mantle, this also serves to reduce the amount of water that can be absorbed.

On the Utah watersheds it is a rare exception if the earth-mantle freezes tight before the snow begins to accumulate. Therefore, when the melting season arrives, the earth-mantle is open and in condition to receive water from the melting snow. For this reason the difference between the amount of moisture present in the earth-mantle when melting begins and the field-capacity of that mantle is a measure of the amount of water required to prime the soil or to bring it up to field-capacity.

It has long been recognized that those watersheds draining glaciated areas show a closer snow-cover-runoff relationship than those watersheds having large areas with deep earth-mantle. A measure of the precipitation which falls as rain before the snow starts to accumulate and during and following the melting season furnishes a poor index because its effectiveness depends so much upon the time and intensity of the storm. For example: On the Logan River Watershed in Utah in the fall of 1939, heavy rains occurred over the State in early September. Following these storms, which ended about September 10, no appreciable precipitation fell for about 90 days.

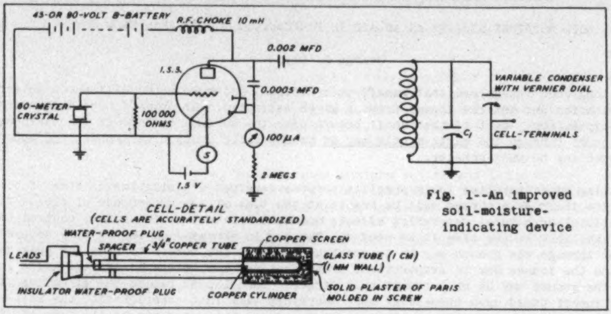

43-OR 90-VOLT B-BATTERY
R.F. CHOKE 10 mH
0.002 MFD
I.S.S.
0.0005 MFD
VARIABLE CONDENSER WITH VERNIER DIAL
80-METER CRYSTAL
100 000 OHMS
100 μA
S
CELL-TERMINALS
C_1
1.5 V
2 MEGS
CELL-DETAIL
(CELLS ARE ACCURATELY STANDARDIZED)
WATER-PROOF PLUG
SPACER
3/4" COPPER TUBE
COPPER SCREEN
LEADS
GLASS TUBE (1 CM)
(1 MM WALL)
INSULATOR WATER-PROOF PLUG
COPPER CYLINDER
SOLID PLASTER OF PARIS MOLDED IN SCREW

Fig. 1--An improved soil-moisture-indicating device

During this interval the watersheds were dried out; springs ceased to flow and when the first snows came on December 20, 1939, they fell on a very dry earth-mantle. Most of the water from the snow-cover which accumulated during the winter of 1939-40 in Utah was used to prime the earth-mantle and never reached the streams. The snow-cover, although fairly heavy on April 1, disappeared rapidly with little increase in runoff. None of the streams yielded a high spring flow and all are now approaching a low-water stage which normally occurs in mid-July.

It is believed that the best index of the water required to prime the soil in any given year is to be found in the amount of moisture present in the soil at the beginning of the accumulation-season and the amount present at the beginning of the melting period. Such an index would not be a measure of quantity of water in acre-feet required to bring the earth-mantle up to field-capacity, but rather an index for correcting the snow-cover-runoff curves, to compensate for varying earth-mantle losses.

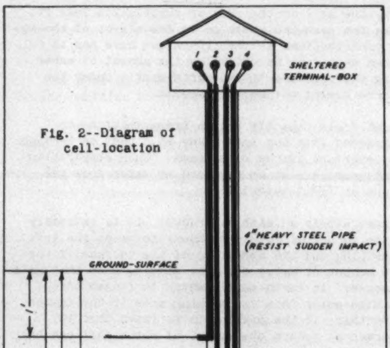

1
2
3
4
SHELTERED TERMINAL-BOX
4" HEAVY STEEL PIPE
(RESIST SUDDEN IMPACT)
GROUND-SURFACE
1'
2'
1'
SMALL CONDUIT-PIPE
CONCRETE
FIXED POST

Fig. 2--Diagram of cell-location

The author has for several years attempted to determine the moisture present in the earth-mantle at the beginning of the winter accumulation-period and also at the beginning of the melting period. Standard methods of determining soil-moisture were used. Both soil-auger and pits were used to get samples. An effort was made to secure samples at the same location each time. Samples were taken at identified points along the snow-courses. Samples taken when a heavy snow-cover lay over the earth-mantle were obtained by first cutting out a snow-core and then inserting a soil-auger in the hole to secure the soil-sample. This method did not prove satisfactory because it was impossible to get the sample out without collecting some snow in it. This difficulty can be overcome by digging down to the ground and then taking the soil-sample in the normal manner. This method, however, is slow and costly.

In an attempt to obtain quickly and fairly accurately a measure of the soil-moisture in the earth-mantle under the snow-cover, attention has been directed to the adaptation of an electrical device based on the principle of capacity to the measurement of soil-moisture. The Fletcher soil-moisture-indicating instrument is a device of this kind. This instrument, based on the principle that the capacity between two plates separated by a porous dielectric depends upon the moisture-content of the dielectric material, was developed by Joel Fletcher of the Soil Conservation Service. The Fletcher instrument, however, was found to be unsuited for the determination of soil-moisture of the earth-mantle under a deep snow-cover and, furthermore, the indicating instrument, being quite delicate and complicated, did not lend itself to being packed about on a man's back.

In cooperation with Clayton Clark and Larry Cole of the Radio Department staff at the Utah State Agricultural College, an instrument based on the same principle as the Fletcher instrument, but radically different in design, has been developed. This instrument shown in Figure 1 is based upon the principle that the capacity between two plates separated by a Plaster of Paris (or some other porous ceramic material) dielectric depends upon the moisture-content of the dielectric material. The instrument provides a means of converting capacity-measurements of a cell which has reached moisture-equilibrium with the soil surrounding it, into moisture-percentage of the soil. The instrument is calibrated to convert the dial-readings to moisture-percentages. Preliminary work indicates that temperature- and conductivity-factors introduce very small errors which can be neglected.

The Utah cell is designed to have a higher leakage-resistance which enables its being buried under heavy snow-cover. It is more permanently sealed against leakage. The porous medium of the cell reaches moisture-equilibrium with the surrounding soil very quickly. The indicating instrument provides a large percentage-change between wet and dry conditions, thus providing for a high degree of sensitivity. The instrument allows for a high ratio between the variable and fixed capacity of the cell. The new type of leads and the frequency used make possible 20 to 30 feet water-proof extensions. This feature is highly desirable where cells are installed under 10 to 20 feet of snow. The indicating instrument is simple to operate and fool-proof. It is light but of rugged construction and is quite inexpensive.

The Utah instrument requires only two controls: An on-off switch and a vernier-dial. To operate, the cell to be measured is connected to the indicating instrument. The condenser is then rotated until the microammeter reads a maximum (a critical but simple adjustment). The dial-reading thus obtained is entered on the calibration-chart which is worked out for the instrument and the soil-moisture is determined. The instrument is balanced by shorting the cell-terminals, setting the dial on zero, and adjusting C to resonance, as indicated by the maximum microammeter-deflection.

A typical field-installation is shown in Figure 2. The cells are placed at different depths in a pit specially prepared for moisture-measurements. In preparing the pit all soil is taken out and the lead-post is set in concrete. All rocks are taken out of soil before it is replaced in the pit. The cells are placed on the pit beginning with the deepest. As each cell is placed it is covered with soil which is firmly packed around it. After all cells are placed, the pit is filled level with the original ground-surface. The leads from the cells end in a terminal-box. After sufficient time has elapsed for the soil-moisture in the pit-soil and the cell to reach equilibrium, the indicating instrument is plugged into the respective cell-leads in the terminal-box and the moisture-content of the soil is determined. This installation permits moisture-determinations to be taken at any time regardless of depth of snow.

The equipment described in the foregoing paragraphs will be installed on the Logan River Watershed during the summer of 1940 and tried out under field-conditions next winter.

Utah State Agricultural Experiment Station,
Logan, Utah

MAP OF WESTERN SNOW-SURVEY SYSTEMS

J. E. Church

The map (Fig. 1 with index), showing snow-survey and forecast-quadrangles, is published to show the progress made in organizing the western watersheds, but particularly to give the general setting of the Humboldt Basin in Nevada and the Yakima, Chelan, and Skagit basins in the Cascade Range, Oregon.

SNOW-SURVEY SYSTEMS ACCOMPLISHED AND PROPOSED FOR THE WESTERN UNITED STATES AND CANADA

(I) SIERRA SYSTEM
- (1) Northern Sierra Quadrangle
- (2) Central Sierra Quadrangle
- (3) Southern Sierra Quadrangle
- (4) Southern California Quadrangle

(II) COLUMBIA SYSTEM
- (7) Upper Columbia Quadrangle
- (8a) Clarks Fork-Pend Oreille Quadrangle
- (8b) Spokane Quadrangle
- (9a) Salmon Quadrangle
- (9b) Upper Snake Quadrangle
- (9c) Lower Snake Quadrangle
- (16) Oregon and Lower Columbia Quadrangle

(III) GREAT BASIN SYSTEM
- (5) Humboldt Quadrangle
- (6) Wasatch Quadrangle

(IV) COLORADO SYSTEM
- (11) Green Quadrangle
- (12) Upper Colorado Quadrangle
- (13) San Juan Quadrangle
- (14) Little Colorado Quadrangle
- (15) Gila Quadrangle

(V) SASKATCHEWAN SYSTEM
- (10) Bow Quadrangle

(VI) MISSOURI SYSTEM
- (17) Upper Missouri Quadrangle (includes International St. Mary - Milk River System)

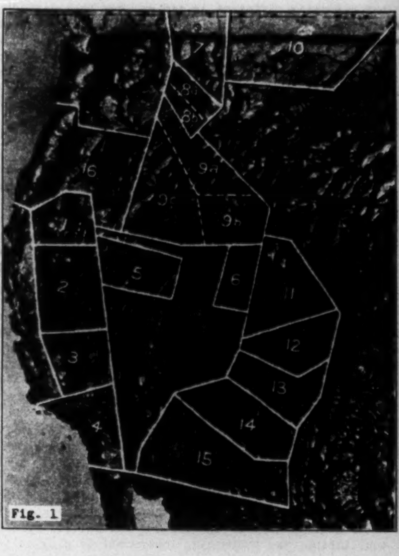


Fig. 1

Nevada Agricultural Experiment Station,
Reno, Nevada

PRESENT TRENDS IN IMPROVING FORECASTING IN THE HUMBOLDT BASIN, NEVADA

Carl Elges

First it might be well to point out a few of the physical features of the Basin. The Humboldt River Basin (see Fig. 1, Snow-Survey Courses of the Nevada Cooperative Snow-Surveys) is a long narrow basin ranging in elevation from less than 4,000 feet to above 11,000 feet and covering in excess of 14,000 square miles. The River is a meandering stream flowing some 900 to 1,000 miles in its 300-mile journey from its source to the Humboldt Sink, its outlet, where its yield is practically zero. At Palisade, the gaging-point, for which the main forecast is made, the normal flow during March to July is considered to be 250,000 acre-feet. The drainage-area above Palisade is over 5,000 square miles and above that point there are some 150,000 acres of irrigated land. Therefore the flow of the River is greatly affected by irrigation-diversions depending upon the character of runoff. The main sources of water are the Charleston-Jarbidge-Jack Creek Mountains in the northern part of the Watershed and the Ruby Mountains in the southern part. The snow-cover in the two areas is not always similar and a lack in the runoff from the north, which normally yields its major flow during April, unduly affects the early runoff in the main Humboldt, for the major flow from the south occurs in late May and early June. The Ruby Mountains yield a very high amount of water, as is shown by Lamoille Creek, a 15,000-acre watershed, of which 10,500 acres are above elevation 8,000 feet, where the flow has been as high as 45,000 acre-feet for the period April to July.

Of primary importance in snow-surveying is the location and representativeness of the snow-courses. Profiles of the water-content on the courses are being drawn to show any irregularities. From the ones already completed it has been found that if irregularities exist they are usually at the beginning or end of the course. After the profiles are drawn and studied a field-inspection is made to determine the causes of the irregularities. Since it has been the practice to inspect the courses both in summer and in winter, nearly always the causes of irregularities are easily found. Most of them are due to topography and wind. In correcting courses measurements can be readily eliminated, for the samples from the remaining points of measurement can be compared with those in past records, which are carefully preserved. However, if a course must be relocated, if possible the best portion of it should be incorporated in the new as a connecting link between the two series. In any case, the old course should be continued for a time for comparison.

After a detailed study of the individual courses, a comparison of each with the runoff from its immediate drainage is highly desirable. However, this can be done in only a few cases since runoff-measurements are usually not available. Nevertheless it is possible to compare each course to the nearest stream having a measured flow. Then the courses should be considered collectively, giving relative weight to the power each has toward producing the resulting runoff. If a course injures the correlation, it should be taken out of the study, but the measurements should be continued until it has been proved conclusively that the course is worthless for it is impossible to fill in a missing record. The flood of February to March, 1910, for which no records exist, is a case in point [see p. 966]. The precipitation was below normal and at the time was practically lacking. For the correlation of snow-cover water-content with runoff, the writer has found the direct method of plotting actual water-content in inches as ordinates and the runoff for the following major water-flow period in acre-feet as abscissae to be the most satisfactory. By this system a forecast-graph is made up for the March 1 snow-surveys and the runoff of March to July. When the April 1 snow-surveys are made they are plotted on the same graph for the same curve, but differing by any change that may occur in water-content from the snowfall of March and by the amount of runoff received at the gaging-station.

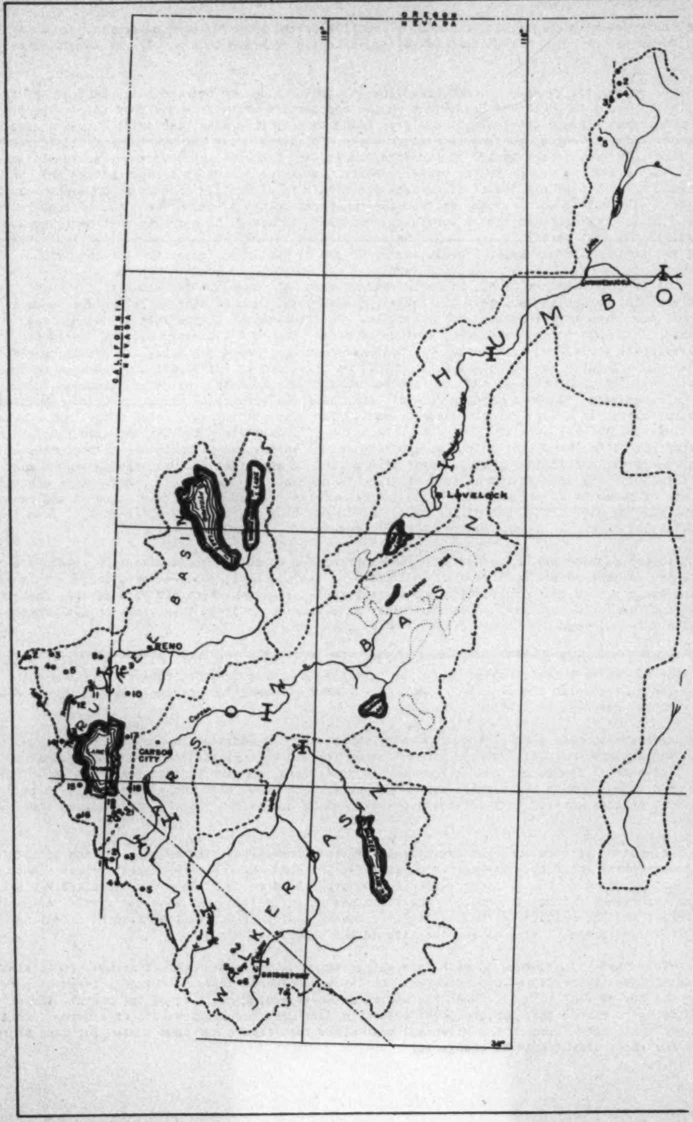
In conjunction with snow-surveying and stream-flow measurements, semimonthly levels are recorded in shallow wells to give an indication of the state of ground-water storage. This year there was a marked deficiency noted and the forecasted flow was therefore reduced from that indicated on the forecast-curve. A careful study will be made to trace the effect of differences in ground-water storage upon total flow.

Records of stream-flow are being extended and when it is felt that reliable forecasts can be made on the main tributaries, it may be possible to make a combined forecast for the main Humboldt by combining the expected flow of the feeder-streams, thus giving a method of checking the general forecast as now made.

Hydrographs have been plotted for each year giving, in addition to the daily flow, the daily mean temperature and daily average precipitation for the several stations. In some cases the yield of some of the summer rain-storms can be determined from the hydrographs. The major runoff and peak-flows seem to be started either by a heavy rain or by high temperatures, but it is doubtful whether satisfactory forecasts of river-stage can be made at the beginning of each season.

It must be pointed out that deviations from the snow-survey figures must be made to obtain any worth-while accuracy. For instance, in 1934, the snow-cover water-content averaged about 59 per cent of normal. Due to a dry watershed and other adverse conditions, the forecast was set at "less than ten per cent of normal." The yield was actually less than four per cent of normal. Therefore one can readily see that a complete understanding of the various factors affecting runoff is desirable in forecasting the flow of the Humboldt.

Since there is a demand to have forecasts given also in percentages of normal, it is planned to retain the figure of 250,000 acre-feet for the period March to July, which is based at present upon the period 1904 to 1927. When discussion arose regarding revision of the normal, the water commissioners stated that 250,000 acre-feet would just meet the requirements of a normal, that is, 100 per cent, irrigation on the River and that since that figure had been quoted for many years they though it undesirable to change it.


OREGON
NEVADA
119°
118°
CALIFORNIA
NEVADA
HUMBO
LOVELOCK
BASIN
RENO
TRUCKEE
BASIN
CARSON CITY
CARSON
BASIN
WALKER
BASIN
BRIDGEPORT
38°

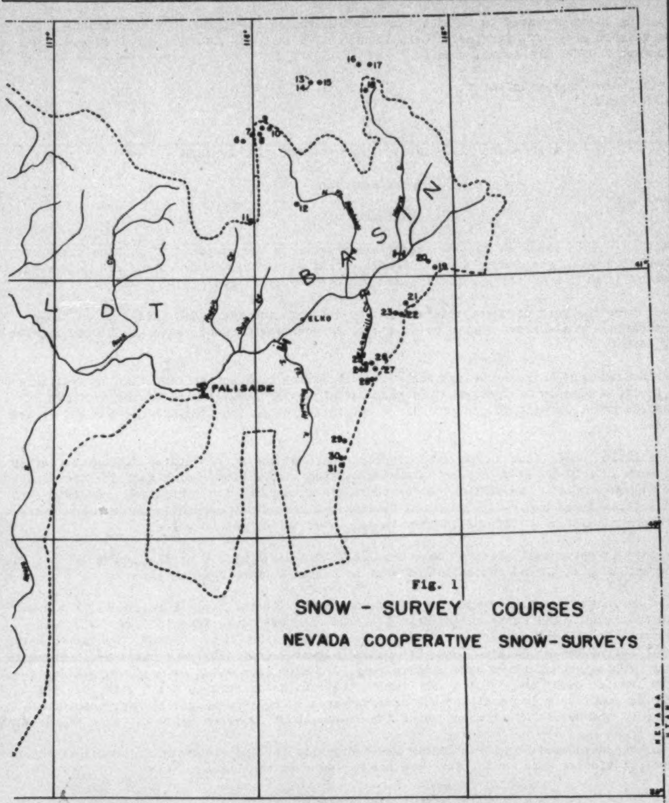


Fig. 1

SNOW - SURVEY COURSES

NEVADA COOPERATIVE SNOW-SURVEYS

TRUCKEE BASIN
1. WEBBER PEAK 8000
2. WEBBER LAKE 7000
3. INDEPENDENCE CREEK 6500
4. INDEPENDENCE LAKE 8200
5. SAGEHEN CREEK 6500
6. SUMMIT 6900
7. SODA SPRINGS 6750
8. GRANITE PEAK 8200
9. BIG MEADOW 8600
10. MT. ROSE 9000 TO 10800
11. BOCA 5900
12. TRUCKEE NO.2 6400
13. TAHOE CITY 6250
14. WARD CREEK 7000
15. RUBICON PEAK 8100
16. LAKE LUCILE 8400
17. MARLETTE LAKE 8000
18. DAGGETTS PASS 7350
19. UPPER TRUCKEE 6400
20. FREEL BENCH 7300
21. HAGAN'S MEADOW 8000

CARSON BASIN
1. CARSON PASS 8600
2. WILLIAMS 7800
3. BURNSIDE LAKE .8000
4. BLUE LAKES 8000
5. SILVER PEAK 8800

WALKER BASIN
1. SONORA PASS 8800
2. LEAVITT MEADOWS 7200
3. WILLOW FLAT 8250
4. BUCKEYE ROUGHS 7900
5. BUCKEYE FORKS 8500
6. CENTER MT. 9400
7. DUNDERBURG PK. 8400

MINOR BASINS
1. MURRAY SUMMIT 6500
(STEPTOE VALLEY)

HUMBOLDT BASIN
1. UPPER BUCKSKIN MT. 8200
2. LOWER BUCKSKIN MT. 6800
3. GRANITE PEAK 8600
4. MARTIN CREEK R.S. 7000
5. LAMANCE CREEK 7000
6. LOWER JACK CREEK 7000
7. UPPER JACK CREEK 7600
8. NORTH FORK 7500
9. RODEO FLAT 7000
10. FRY CREEK 6800
11. TAYLOR CANYON 5200
12. TREMEWAN'S RANCH 5600
13. GOLD CREEK (OLD) 6800
14. BIG BEND 6800
15. GOLD CREEK R.S. 6800
16. BEAR CREEK 8100
17. FOX CREEK 6900
18. MARYS RIVER 8500
19. TROUT CREEK 8500
20. TROUT CREEK 6900
21. DORSEY BASIN 7900
22. DRY CREEK 6500
23. RYAN RANCH 5775
24. THOMAS CANYON 9000
25. LAMOILLE CREEK 7400
26. LAMOILLE CREEK 7600
27. LAMOILLE CREEK 8100
28. LAMOILLE CREEK 9000
29. GREEN MT. 7700
30. HARRISON PASS 6600 & 7400
31. CORRAL CANYON 7500

In closing it is encouraging to note that the studies on the Humboldt are apparently leading toward greater accuracy, for preliminary figures show that the forecast for 1940 was less than one per cent under the actual runoff.

Nevada Agricultural Experiment Station,
Reno, Nevada

A PROPOSED SNOW-SURVEY SYSTEM FOR THE YAKIMA BASIN

H. P. Boardman

Introduction

The title of this paper is to some extent a misnomer, as the proposal of a "Snow-survey system" should certainly depend to a considerable extent on a field-study of the drainage-area and such study or even a cursory inspection has not been my privilege.

However some analysis of precipitation- and runoff-data for the Basin (see Fig. 1) shows that comprehensive snow-surveys should be an aid to forecasting probable water-supply during the irrigating season.

One main advantage of snow-surveys for such forecasting lies in the fact that an available supply in the form of snow on the ground is measured at about the beginning of the melting season, whereas merely precipitation-records do not tell the residue available at the end of the winter season.

The available runoff-data in the Water-Supply Papers of the United States Geological Survey cover the years 1906/07 to 1936/37 for the gaging-station at Cle Elum, which is below the junction of the Cle Elum River with the Yakima. While there are diversions for irrigation and controlled storage in several lakes above Cle Elum, the published data include corrections for such diversions and storage. The tributary drainage-area is stated as 500 square miles.

While this is but a small part of the complete Yakima Basin, it is at the headwaters and its forecasting should give a good indication of what to expect further down stream.

In this Basin the Weather Bureau precipitation-records for the three most significant stations--Lake Keechelus, Lake Kachess, and Lake Cle Elum--are available from 1908/09, so it was decided to consider in this analysis only the 29-year period 1908/09 to 1936/37, the latter being the last year for which the United States Geological Survey runoff-data were published. The data from other precipitation-stations were used, namely, Cle Elum (for which records are available from January 1899 to date) and Bumping Lake (where the continuous records begin with July 1911). Bumping Lake is about 20 miles south of the drainage-area of 500 square miles under consideration and tributary to the Naches River which joins the Yakima about 50 miles below the gage at Cle Elum.

Normals were developed for the selected 29-year period for the river-runoff at Cle Elum and for the precipitation at each of the five Weather Bureau stations listed.

Percentage-system

A quantitative estimate of the water-supply from a given basin would require numerous measuring stations for either general precipitation or snow-survey as the case might be, including several near-maximum altitudes, close to the divide. Such installation and operation would usually entail prohibitive costs. In the case of the Basin under consideration, the runoff-records indicate that the precipitation in the upper altitudes, above Lake Keechelus, is very much greater than at that station which averages 65.2 inches per year for the 29 calendar years 1909-37, being greater than at any other Weather Bureau station in the Yakima Basin.

Suppose the actual quantity of water precipitated on a watershed during a certain interval of time, or the actual water-content of the snow lying on a watershed at a given date, was possible of determination, who can tell how much will run off on the surface and how much will be lost by absorption?

The above indicates the argument for comparing the different years or corresponding portions of different years by the method of percentage of normal, both in the matter of precipitation or snow-survey and also runoff. It is found, for instance, that the relative precipitations at

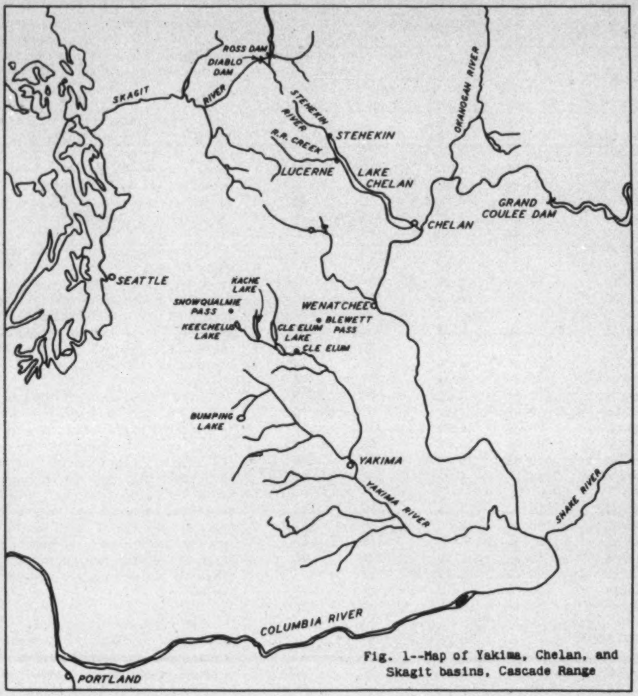

ROSS DAM
DIABLO DAM
SKAGIT
RIVER
STEHEKIN RIVER
STEHEKIN
R.R. CREEK
LUCERNE
LAKE CHELAN
OKANOGAN RIVER
GRAND COULEE DAM
CHELAN
SEATTLE
KACHE LAKE
SNOWQUALMIE PASS
KEECHELUS LAKE
CLE ELUM LAKE
CLE ELUM
WENATCHEE
BLEWETT PASS
BUMPING LAKE
YAKIMA
YAKIMA RIVER
SNAKE RIVER
COLUMBIA RIVER
PORTLAND

Fig. 1--Map of Yakima, Chelan, and Skagit basins, Cascade Range

different stations, that is, the percentages of normal are usually quite similar. This is of course dependent on the extent of the storms bringing the precipitation, and generally the heavier storms are quite wide-spread in extent.

Normals

The above leads up to the question of normals. Quite generally in the past the average over a period of years has been taken as the normal. For many years the United States Weather Bureau followed the practice of using the average for all of the years of record as a normal after a certain minimum number of years of record was available. This gave a changing value to the normal for any station and the normals for different stations were not fairly comparable unless the same period of years was involved in the determinations.

A number of articles have been written advocating the use of the median instead of the average as a normal. I decided that this was a good time to try it out.

Where an even number of years is involved, the median might obviously be any value such that there was the same number of years with values of the function above as with values below that median, so to determine a definite value I decided that the average of the four values nearest the median, that is, two above and two below, would be a fair value for a normal.

Where an odd number of years is involved, one actual value is a median, but since this value may be rather eccentric relative to the next above and the next below I concluded that a fairer

Table 1--Precipitation-data

Year	Precipitation		Per cent of 29-year normal	
	December to March	April to June	December to March	April to June
	inches	inches		
BUMPING LAKE				
Normals	24.00	4.50		
1911/12	20.92	1.30	87	29
1912/13	23.69	4.03	99	90
1913/14	22.14	4.61	92	102
1914/15	12.28	6.31	51	140
1915/16	38.44	5.55	160	123
1916/17	17.54	7.72	73	172
1917/18	45.13	3.03	188	67
1918/19	32.13	4.28	134	95
1919/20	18.95	5.46	79	121
1920/21	33.65	6.61	140	147
1921/22	18.85	2.17	79	48
1922/23	33.46	5.34	139	119
1923/24	23.34	2.84	97	63
1924/25	25.55	3.99	106	89
1925/26	15.97	3.88	67	86
1926/27	28.49	4.79	119	106
1927/28	23.60	3.50	98	78
1928/29	15.58	6.38	65	142
1929/30	24.17	4.35	101	97
1930/31	22.62	6.66	94	148
1931/32	30.25	5.00	126	111
1932/33	27.86	6.20	116	138
1933/34	48.34	4.32	201	96
1934/35	30.40	2.69	127	60
1935/36	30.59	4.13	127	92
1936/37	24.17	10.29	101	229
LAKE KEECHELUS				
Normals	35.00	7.20		
1908/09	32.00	6.83	91	95
1909/10	40.01	10.36	114	144
1910/11	20.85	4.42	60	61
1911/12	30.02	6.43	86	89
1912/13	38.17	6.94	109	96
1913/14	31.31	6.59	89	92
1914/15	13.26	8.01	38	111
1915/16	50.34	9.00	144	125
1916/17	35.19	12.39	101	172
1917/18	61.09	5.30	175	74
1918/19	45.67	8.48	130	118
1919/20	26.12	8.71	75	121
1920/21	43.01	10.19	123	142
1921/22	27.85	7.04	80	98
1922/23	42.49	7.36	121	102
1923/24	32.52	5.30	93	74
1924/25	31.95	4.46	91	62
1925/26	29.52	5.80	84	81
1926/27	32.77	8.59	94	119
1927/28	30.24	10.83	86	150
1928/29	31.26	10.85	89	151
1929/30	34.19	6.78	98	94

normal would often be obtained by using the average of the five values nearest to the median, that is, the actual median and two above and two below.

This practice was followed in the matter of runoff-data except that all of these normals in acre-feet units end in at least two ciphers, the smallest value involved being 24,400 acre-feet--the 29-year normal for runoff of September.

Substantially the same practice was followed for precipitation, though in several cases the normal was moved somewhat towards the average, but always closer to the median than the average. In inches of precipitation the normals all end with a cipher in the second decimal place.

The impression conveyed by critics of the "average for normal" is that the high values have more effect on the average than do the low values. For instance, we may have above 200 per cent of normal but never below zero per cent--often above 160 per cent but very seldom below 40 per cent. This relationship is quite general but it sometimes happens that the median, or normal close to the median, is greater than the average.

In the cases of runoff- and precipitation-data, the excess of average over median usually is less pronounced for annual and for groups of several months than where the records of a single month are under consideration. For instance, the 29-year average annual precipitation at Lake Keechelus, as before mentioned, is 65.2 inches. The median for these 29 years is 64.8 inches and the normal as determined by averaging the five years nearest to the median is 64.0 inches. Generally the normal so determined is closer to the median than in this case. The difference between normal and average in this case is less than two per cent.

The 29-year average runoff at Cle Elum for November is 101,170 acre-feet; the median is 72,800; and the normal, determined by averaging the middle five, is the same--72,800 acre-feet. Here the difference between median or normal and the average is 28 per cent of the average or 39 per

Table 1--Precipitation-data--Continued

Year	Precipitation		Per cent of 29-year normal	
	December to March	April to June	December to March	April to June
	inches	inches		
LAKE KEECHELUS--Continued				
1930/31	27.23	11.04	78	153
1931/32	47.50	6.33	136	88
1932/33	46.77	7.14	134	99
1933/34	66.07	6.49	189	90
1934/35	46.68	5.07	133	70
1935/36	44.62	9.08	127	126
1936/37	36.09	15.08	103	209
LAKE KACHESS				
Normals	29.00	5.50		
1908/09	26.00	4.51	90	82
1909/10	33.79	5.87	117	107
1910/11	19.81	5.41	68	98
1911/12	26.22	5.51	90	100
1912/13	27.01	3.41	93	62
1913/14	17.46	6.28	60	114
1914/15	10.18	5.05	35	92
1915/16	33.31	5.12	115	93
1916/17	28.74	7.02	99	128
1917/18	47.45	4.72	164	86
1918/19	37.89	5.71	131	104
1919/20	19.79	7.22	68	131
1920/21	37.04	8.40	128	153
1921/22	19.30	4.64	67	84
1922/23	34.47	5.16	119	94
1923/24	27.08	4.11	93	75
1924/25	29.01	5.02	100	91
1925/26	21.91	4.50	76	82
1926/27	25.10	7.08	87	129
1927/28	29.19	7.18	101	131
1928/29	21.27	7.70	73	140
1929/30	30.33	5.78	105	105
1930/31	19.17	9.05	66	165
1931/32	40.52	4.20	140	76
1932/33	39.86	6.39	137	116
1933/34	56.85	3.76	196	68
1934/35	39.86	4.57	137	83
1935/36	42.43	6.68	146	121
1936/37	30.99	11.73	107	213
LAKE CLE ELUM				
Normals	19.70	3.50		
1908/09	10.29	1.67	52	48
1909/10	24.13	3.36	122	96
1910/11	9.75	3.82	49	109
1911/12	15.11	3.58	77	102
1912/13	24.24	2.70	123	77
1913/14	17.26	2.85	88	81
1914/15	8.64	2.17	44	62
1915/16	19.56	1.98	99	57
1916/17	14.93	4.24	76	121
1917/18	43.23	3.41	219	97
1918/19	27.86	3.11	141	89
1919/20	13.96	3.73	71	107

cent of the normal. The 29-year results for both runoffs of May and June yield median, and likewise normal, a little above the average.

It may be worth pointing out here that for a group of months, as December to March, the sum of the separate monthly medians is not the same as the median of the sums of the same group for the same period of years. The same statement applies to the normals as here determined. However the sum of the averages is the same as the average of the sums.

Precipitation versus runoff

Where snow is an important part of the precipitation in our north temperate zone the majority of it falls in the months of December to March, so in this analysis the precipitation of December to March is related to the runoff of April to July. July is the minimum month of precipitation at the stations at Lakes Cle Elum, Kachess, and Keechelus, and at Keechelus--the wettest of all--the July average is less than one inch. Since the normal runoff of July, while much less than that of June, is more than the combined normals of August and September, it is probable that some melting-snow effect carries over into July. May is normally the heavy month of runoff but sometimes June and, in several years, April exceeded May in runoff.

Table 1 shows the precipitation of December to March in both inches and per cent of normal, and similarly the precipitation of April to June for the five Weather Bureau stations previously listed--the Bumping Lake data starting with 1911/12 while all of the others start with 1908/09.

Table 3 gives the runoff-values for each month of the 29 years as well as the annual totals and the totals for April to July and percentages of normal, and also the totals for December to March and percentages of normal. At the end of Table 3 are shown the averages by month, year, and group, medians, and normals.

In relating the precipitation of December to March to the runoff of April to July, it was thought best to average the percentages of normal precipitation for all five stations. Table 2 shows this relationship in figures and also shows the precipita-

Table 1--Precipitation-data--Concluded

Year	Precipitation		Per cent of 29-year normal	
	December to March	April to June	December to March	April to June
	inches	inches		
LAKE CLE ELUM--Continued				
1920/21	26.47	5.66	134	162
1921/22	11.53	2.40	59	69
1922/23	26.35	4.83	134	138
1923/24	16.62	2.91	84	83
1924/25	23.34	3.39	118	97
1925/26	18.93	3.38	96	97
1926/27	20.04	5.22	102	149
1927/28	20.01	5.81	102	166
1928/29	15.50	6.46	79	185
1929/30	20.95	3.72	106	106
1930/31	14.35	6.94	73	198
1931/32	25.33	2.74	129	78
1932/33	19.69	3.66	100	105
1933/34	36.91	1.67	187	48
1934/35	23.65	1.32	120	38
1935/36	25.24	4.68	128	134
1936/37	19.13	7.83	97	224
CLE ELUM				
Normals	11.70	2.80		
1908/09	10.27	1.00	88	36
1909/10	11.10	2.67	95	95
1910/11	7.92	3.72	68	133
1911/12	14.09	4.28	120	153
1912/13	12.56	2.91	107	104
1913/14	8.05	3.36	69	120
1914/15	6.15	3.23	53	115
1915/16	18.52	2.88	158	103
1916/17	13.45	3.31	115	118
1917/18	22.51	2.43	192	87
1918/19	18.81	1.44	161	51
1919/20	8.34	3.08	71	110
1920/21	18.88	3.71	161	132
1921/22	8.75	1.19	75	43
1922/23	19.81	3.25	169	116
1923/24	14.02	1.55	120	55
1924/25	10.91	3.13	93	112
1925/26	9.37	1.76	80	63
1926/27	11.99	4.04	102	144
1927/28	10.78	2.60	92	93
1928/29	7.70	2.57	66	92
1929/30	8.19	0.40	70	14
1930/31	7.56	4.56	65	163
1931/32	15.11	1.44	129	51
1932/33	11.96	1.45	102	52
1933/34	22.76	0.54	195	19
1934/35	14.13	1.64	121	59
1935/36	13.59	5.58	116	199
1936/37	10.07	5.50	86	196

tion of April to June, which has some effect on runoff of April to July. In this spring and summer precipitation-column, Cle Elum precipitation-data were omitted, being quite small and, it was thought, not deserving of much weight. Likewise the precipitation for July was omitted as it is usually very small and probably contributes little to stream-flow.

Figure 1 shows the data given in Table 2 arranged graphically and chronologically.

Figure 2 shows graphically the relationship of precipitation of December to March to runoff of April to July for each of the 29 years.

An examination of Table 2 and both Figures 2 and 3 shows that for many years the runoff of April to July in percentage of normal did not check closely with the precipitation of December to March. A study of Weather Bureau records helps to explain many of the most discordant years, a few of which will be discussed in detail.

Years in which the runoff of April to July was relatively low:

1917/18--Warm December and January with heavy rains especially in December and excessive runoff, that for December being 5.6 times normal and for January being 3.7 times normal. This high winter runoff left much less snow to furnish runoff in April to July than would have been expected had all of the winter precipitation been in the form of snow.

1918/19--Similar conditions though not so excessive winter rains and runoff as in 1917/18.

1919/20--High runoff in January caused by rain accompanied by chinook. The runoff of April to July would have been less had there not been quite heavy rains in April.

1920/21--Similar winter rains and late melting in March increased the winter runoff and lowered the spring runoff in spite of precipitation in April.

Several other years of relatively low runoff during April to July are explainable in the same manner and notably the year 1933/34, when the temperature was relatively high all winter and exces-

Table 2--Relation of precipitation and runoff

(All in per cent of normal)

Year	December to March precipitation (A)	April to July	April to June
		Runoff (B)	Precipitation (C)
1908/09	80	97	75
1909/10	112	107	116
1910/11	61	84	89
1911/12	92	102	80
1912/13	106	140	81
1913/14	80	97	97
1914/15	44	51	101
1915/16	135	167	100
1916/17	93	141	148
1917/18	188	92	81
1918/19	139	110	102
1919/20	73	64	120
1920/21	137	122	151
1921/22	72	88	75
1922/23	136	113	113
1923/24	97	84	74
1924/25	102	107	85
1925/26	81	51	87
1926/27	101	115	126
1927/28	96	96	131
1928/29	74	89	154
1929/30	96	72	100
1930/31	75	77	166
1931/32	132	120	88
1932/33	118	132	115
1933/34	194	82	76
1934/35	128	97	63
1935/36	129	138	118
1936/37	99	111	219

(A) = Average of per cent of normal for all five Weather Bureau stations, namely: (1) Bumping Lake (3,400 feet); (2) Lake Keechelus (2,479 feet); (3) Lake Kachess (2,270 feet); (4) Lake Cle Elum (2,200 feet); and (5) Cle Elum (1,930 feet).

(B) = Runoff of Yakima River at gaging-station at Cle Elum; drainage-area, 500 square miles.

(C) = Average of per cent of normal for first four stations of (A).

sive and damaging floods occurred from rains in December. That spring April was the month of high runoff, being more than 190 per cent of normal, but runoff during May, June, and July were all far below normal, bringing the total runoff for April to July down to 82 per cent of normal.

An attempt has been made to adjust some of the points on graph (Fig. 2) to a condition of all precipitation for December to March being in the form of snow by assuming that the excess of winter runoff usually caused by winter rains or high temperature, should be moved ahead and added to the actual runoff during April to July.

Years in which the runoff during April to July was relatively high

A quantitative estimate of the correction to be applied is not always so easy as in the case of relatively low runoff of April to July:

1908/09--There was probably some snow in late November which carried over through the winter. The precipitation during the winter was 80 per cent of normal while runoff was only 50 per cent of normal, thus leaving more for runoff during the summer.

1910/11--Heavy precipitation in November, part of which was probably snow, though runoff during November was also high. Satisfactory explanation is not evident.

1912/13--Precipitation in November but little above normal and runoff in November about 90 per cent. Runoff in winter was 79 per cent. This deficiency of runoff during November to March brought back from the actual runoff of April to July would still leave a considerable excess of runoff during April to July over what should have been realized from the winter precipitation, in spite of a subnormal precipitation during April to June.

1915/16--Several degrees subnormal temperature and heavy precipitation in November doubtless brought some snow. Precipitation during December to March 135 per cent and runoff only 98 per cent also left a larger proportion to runoff in April to July.

1916/17--Cold November with nearly normal precipitation, probably largely snow. Runoff during November to March only 57 per cent of normal, while precipitation during December to March of 93 per cent left extra runoff for April to July.

Weather Bureau data furnish the means of partially explaining the discrepancies of other years.

Doubtless heavy rains in the fall store up some ground-water which contributes to the runoff in April to July following.

Snow-surveys made about April 1 would give a good idea of the left-over storage above ground and would help materially in forecasting the available supply, but records during fall and winter, as to both precipitation and runoff, should also be given consideration.

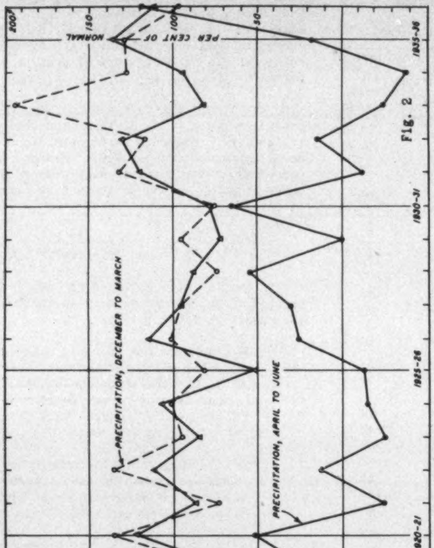


Fig. 2

Abnormal temperatures, high or low, also have a marked effect. For instance, there was practically no precipitation in June, 1922, but the monthly temperature was 4° to 7° above normal and the runoff was 112 per cent of normal, while the total runoff during April to July was only 88 per cent of normal. Rapid melting of snow increases the amount of water-yield by concentrating the flow into streams and decreasing the time allowed for percolation and evaporation, though it increases rate of evaporation.

Table 3--Runoff in acre-feet of Yakima River, Washington, at Cle Elum Gage

(Drainage-area, 500 square miles)

Year Month	1908/09	1909/10	1910/11	1911/12	1912/13	1913/14	1914/15	1915/16
October	28700	28800	124000	21100	34500	73900	48600	48900
November	65400	348000	197000	188000	65800	80100	142000	78800
December	43400	152000	70700	83100	61600	47300	48600	64800
January	45400	71800	68900	92600	71900	102000	26200	41400
February	33400	50500	32500	85200	80800	44300	21500	48600
March	57600	254000	72700	53900	70000	131000	90900	198000
April	129000	302000	139000	149000	179000	235000	218000	247000
May	243000	341000	227000	355000	363000	308000	108000	361000
June	306000	149000	233000	240000	402000	166000	54500	451000
July	103000	65900	76300	75300	182000	73300	31300	281000
August	35800	23400	28900	34700	50900	26400	21100	89100
September	28500	23000	40900	29200	37600	26600	14200	37700
Annual	1120000	1815000	1313000	1403000	1600000	1310000	825000	1950000
Dec.-Mar.	179800	528300	244800	314800	284300	324600	187200	352800
Apr.-July	781000	857900	675300	819300	1126000	782300	411800	1340000
Per cent of normal	97	107	84	102	140	97	51	167

Year Month	1916/17	1917/18	1918/19	1919/20	1920/21	1921/22	1922/23	1923/24
October	23700	21900	71500	23700	130000	67200	25100	35400
November	41300	29200	70800	120000	78000	72800	39100	56000
December	35800	447000	187000	89400	82600	290000	70900	94100
January	52600	283000	132000	148000	143000	41000	176000	80200
February	73200	86000	59900	72600	140000	25700	40500	193000
March	44800	64800	65000	78400	155000	27800	65700	85900
April	95300	180000	212000	98000	175000	93400	235000	135000
May	354000	242000	315000	192000	350000	293000	329000	355000
June	417000	244000	233000	151000	337000	266000	239000	133000
July	269000	76100	122000	71600	121000	53000	109000	55000
August	57300	42500	41000	35000	36000	27000	8000	27000
September	26800	21400	25600	68300	45500	24800	12000	20100
Annual	1490000	1740000	1530000	1150000	1790000	1280000	1350000	1270000
Dec.-Mar.	206400	880800	443900	388400	520600	384500	353100	453200
Apr.-July	1135300	742100	882000	512600	983000	705400	912000	678000
Per cent of normal	141	92	110	64	122	88	113	84

Year Month	1924/25	1925/26	1926/27	1927/28	1928/29	1929/30	1930/31	1931/32
October	50100	25600	89800	120000	65000	9800	33400	59800
November	61900	36000	76800	229000	38800	13200	43000	78200
December	171000	152000	115000	159000	32600	31700	24700	47900
January	76200	82300	55200	172000	22700	30100	49200	82900
February	112000	70400	40100	44900	20800	103000	71100	132000
March	98300	52000	54900	135000	72100	124000	114000	218000
April	239000	200000	154000	150000	106000	256000	167000	233000
May	368000	129000	307000	391000	316000	175000	296000	336000
June	182000	57000	358000	167000	218000	105000	124000	283000
July	70900	27000	105000	62600	76000	47300	33500	110000
August	26000	18200	33000	22000	30000	24700	6000	41300
September	19400	24600	45500	14200	14200	13700	9800	23600
Annual	1470000	974000	1430000	1670000	1010000	934000	972000	1650000
Dec.-Mar.	457500	456700	265200	510900	148200	288800	259000	480800
Apr.-July	859900	413000	924000	770600	71600	583300	620500	962000
Per cent of normal	107	51	115	96	89	72	77	120

Table 3--Runoff in acre-feet of Yakima River, Washington, at Cle Elum Gage--Concluded
(Drainage-area, 500 square miles)

Year / Month	1932/33	1933/34	1934/35	1935/36	1936/37	For 29 years Average	For 29 years Median	For 29 years Adopted normal
October	47600	188800	94000	20100	18200	56180	47600	43000
November	282000	179900	183600	27100	12100	101170	72800	72800
December	154000	448400	113300	29600	71000	117900	82600	79400
January	140000	233100	230600	52600	30100	97690	76200	76500
February	44900	138000	115300	40300	36600	70940	59900	60100
March	54000	282000	99800	93600	70900	106350	85900	84300
April	155000	332000	120900	274800	135200	184300	175000	171200
May	286000	199800	309600	495300	312700	298530	312700	312300
June	402000	92600	253100	268500	348400	237250	239000	237800
July	216000	38800	100800	72500	100900	97450	76000	75400
August	67300	22400	40100	26200	29900	33490	29900	29800
September	55000	23400	29100	16400	15800	27130	24600	24400
Annual	1900000	2179000	1690000	1417000	1182000	1428100	1477000	1414000
Dec.-Mar.	392900	1101500	559000	216100	208600	392852	353100	361000
Apr.-July	1059000	663200	784400	1111100	897200	817520	784400	805000
Per cent of normal	132	82	97	138	111			

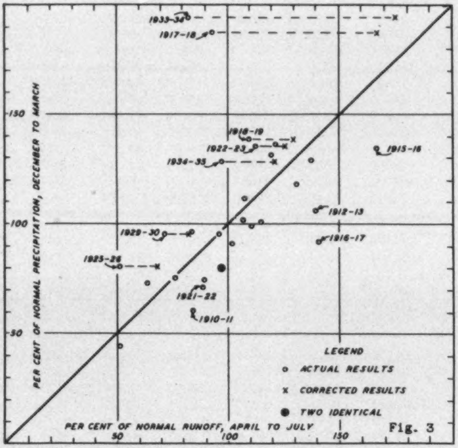


Fig. 3

Abnormally high or low precipitation during April to June often has a marked effect on the runoff, but in this analysis this factor has not been of as much help as was expected in explaining discrepancies.

University of Nevada,
Reno, Nevada

DISCUSSION

LAWRENCE C. FISHER (Meteorologist in Charge, United States Weather Bureau, Seattle, Washington; communicated)--Snow-density measurements have been made in the Yakima Basin for many years. The observer at the Bureau of Reclamation Station at Bumping Lake has been most regular with these observations. Density-observations were also made at Lake Kachess. Each spring the City of Seattle makes a survey of snow for the Cedar Lake Drainage-Basin and the observer makes density-measurements toward the end of March each year in Snoqualmie Pass near our mountain snowfall-station. You will find these records scattered through the snowfall-bulletins. It is my understanding that Mr. Jessup, formerly of the Bureau of Agricultural Engineering, now the Soil Conservation Service, made some surveys in the Yakima Basin. The data therefrom have been included in the larger bulletin covering the Columbia Basin.

No doubt you are familiar with the fact that the personnel for the Columbia Hydrologic District has been selected and is now preparing to secure data on water-resources in the Columbia Basin on a much larger scale than has heretofore been possible. As soon as the necessary instrumental equipment becomes available after July 1, they will proceed to the establishment of stations equipped with a view to obtaining snowfall-measurements and water-contents in places in the mountains that are uninhabited and to obtaining rates of rainfall at stations where there is personnel.

JAMES C. MARR (Division of Irrigation, Soil Conservation Service, Boise, Idaho, letter March 19)--The snow-survey summaries of the Yakima and Wenatchee basins for 1938 and 1939 show snow-survey courses for the entire winter of 1938 at Bumping Lake (elevation 3,450 feet) and for May at Blewett Pass (4,270 feet). In 1939, records were obtained also at Lake Cle Elum (2,200 feet) during March to May and at Fog Basin (5,600 feet) during April to May. Several more courses in Yakima and adjacent watersheds were surveyed tentatively by Mr. Jessup and his cooperators, but were discarded as unsuitable. Mr. Jessup intended establishing about five new courses in Yakima and adjacent drainages last fall, but his death prevented. We will fill our Yakima post this spring and will be prepared to augment the present program in Washington State--at least for the area westward from Cascade Mountains. Mr. Jessup had full charge of our snow-surveys in Washington and was the only one who had complete knowledge of them. Our work there has suffered a serious set-back because of his death. Much of my time next summer must be spent in that territory to put the snow-survey activity back where it was before Mr. Jessup died. You will, I am sure, excuse our inability to provide the historical background for snow-surveys on Yakima Drainage for which you asked. Reservoir superintendents of the Bureau of Reclamation make the surveys at Bumping Lake and Lake Cle Elum. We now receive the data for these two courses through the office of Mr. Moore, Superintendent of the Yakima Project.

E. H. COLLINS (Assistant Chief Engineer, Washington Water Power Company, Spokane, Washington; communicated)--Unfortunately, absence from my office and many urgent matters have prohibited making any suggestions relative to your problem. Personally I have felt that our records were not of sufficient length as yet to spend much time digesting them to draw conclusions as to the value of snow-survey work. However, I do believe that as soon as we have had records for a sufficient number of years in the Chelan Basin, they should show very conclusively the value of snow-survey in power-development, or the value of snow-survey in the generation of hydroelectric power. The following summary may be of interest:

REPORT ON SNOW-SURVEYS OF 1939 IN THE CHELAN BASIN

Since the report for 1939 contains the summary of nine winters' data with a wealth of material on the depth, density, and water-content of the snow and method of forecasting the run-off, it is herewith reproduced as an important link in the study of the feasibility of basing forecasts of the streams of the Cascade Range on the residual snow-cover. An earlier paper on winter precipitation versus snow-survey for forecasting on the Skagit River, Washington, has been printed [Trans. Amer. Geophys. Union, 1938, pp. 695-702].

(The special feature in forecasting the levels of Lake Chelan is the use of the quantitative method of snow-surveying as a basis for forecasting lake-levels by the percentage-method.--Editor.)

Counting this year's records, nine different winters' data have been secured on the weight and depth of the snow in the Chelan Basin. The field-work was done by C. R. Meils and W. E. Johnson of the Engineering Department, and G. R. Imus of Stehekin, with the exception of three courses in the Upper Bridge Creek country, which were measured by Fred Stillwright of Twisp, Washington. The survey occupied March 20 to April 2, 1940. The party traveled by automobile to Chelan and by boat on Lake Chelan to Lucerne near the head of the Basin.

Table 1--Summary, Chelan Basin Snow-Survey, 1939

Basin	Course	Date	Elevation	Depth	Core	Density	Water-content	Precipitation-correction to April 1	Total water-content, April 1
		1939	feet	inches	inches	o/o	inches		inches
Railroad Creek	Two Mile	Mar. 22	2,020	18.1	14.2	40.3	7.3	0	7.3
	Seven Mile	Mar. 22	3,015	47.4	41.9	37.8	17.9	0	17.9
	Greenwood	Mar. 23	3,540	41.7	35.3	38.4	16.0	0	16.0
	Little Meadows	Mar. 24	5,275	85.4	81.4	43.7	37.3	0	37.3
	Lyman Lake	Mar. 25	5,900	135.5	130.7	44.1	59.8	0	59.8
	Cloudy Pass	Mar. 25	6,500	100.0	92.0	46.0	46.0	0	46.0
Stehekin River	Bullion	Mar. 28	1,460	6.8	5.9	41.2	2.8	0	2.8
	Bridge Creek	Mar. 29	2,100	40.5	37.2	38.0	15.4	0	15.4
	Park Creek Flat	Mar. 31	2,200	61.6	56.2	38.6	23.8	0	23.8
	Pass Creek	Mar. 28	2,500	52.0	45.4	36.2	18.8	0	18.8
	Cottonwood	Mar. 31	2,500	68.2	64.2	37.7	25.7	0	25.7
	Bridge Creek Trail	Mar. 29	2,680	49.6	45.1	37.1	18.4	0	18.4
	Peterson's	Mar. 30	3,730	64.1	57.3	36.8	23.6	0	23.6
	Upper Meadows	Mar. 27	4,400	86.7	78.2	39.9	34.6	0	34.6
	Park Creek Ridge	Mar. 30	4,600	88.4	84.0	40.7	36.0	0	36.0
	Rainy Pass	Mar. 31	4,780	88.6	84.2	39.6	35.1	0	35.1
	Dagger Lake	Mar. 29	5,200	103.7	95.4	42.0	43.6	0	43.6
	Agnes Creek	Mar. 26	5,400	125.9	123.0	43.4	54.6	0	54.6

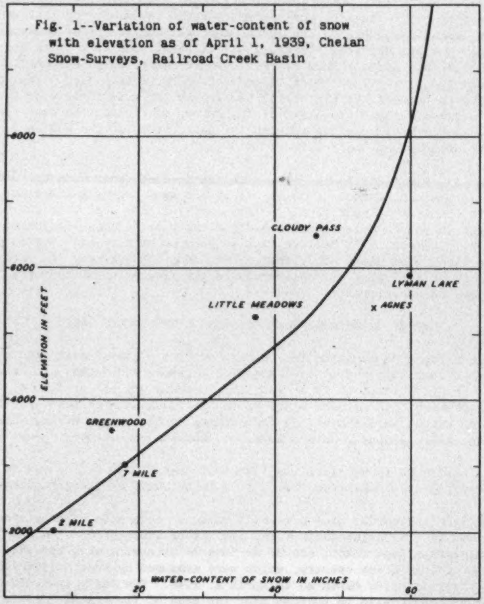


Fig. 1--Variation of water-content of snow with elevation as of April 1, 1939, Chelan Snow-Surveys, Railroad Creek Basin

Table 2--Comparison of water-content of snow as of April 1, 1927-31, and 1936-39, Chelan Lake Basin Snow-Surveys

Basin	Course	Ele-vation	Water-content of snow in inches for year									9-year average
			1927	1928	1929	1930	1931	1936	1937	1938	1939	
		feet										
Railroad Creek	Two Mile	2,020	11.1	4.8	4.9	5.0	5.1	12.0	11.0	12.8	7.3	8.2
	Seven Mile	3,015	22.5	15.3	11.9	15.8	13.2	23.0	20.1	24.3	17.9	18.2
	Greenwood	3,540	24.4	16.4	11.7	15.7	17.1	21.3	23.8	29.8	16.0	19.4
	Little Meadows	5,275	40.4	30.7	25.0	30.6	30.0	46.5	36.6	55.3	37.3	36.9
	Lyman Lake	5,900	(53.3)	50.1	35.5	45.1	38.3	57.0	46.9	67.3	59.8	50.4
	Cloudy Pass	6,500	42.1	41.8	23.2	34.2	32.8	43.0	36.0	56.0	46.0	39.5
	Average		32.3	26.5	18.7	24.4	22.8	33.8	29.1	40.9	30.7	28.8
Stehekin River	Bullion	1,460	10.7	3.2	0.0	0.9	0.7	10.3	8.3	15.9	2.8	5.9
	Bridge Creek	2,100	22.9	15.5	8.9	16.2	15.3	24.7	19.2	28.4	15.4	18.5
	Park Creek Flat	2,220	28.7	21.8	14.9	24.1	22.3	32.6	27.0	37.2	23.8	25.8
	Pass Creek	2,500	....	20.0	13.6	20.1	19.5	31.6	25.4	38.9	18.8	23.5[a]
	Cottonwood	2,500	36.2	27.6	19.4	27.2	28.1	36.4	28.6	38.8	25.7	29.7
	Bridge Creek Trail	2,680	27.8	20.6	14.5	21.3	21.1	33.0	25.4	32.6	18.4	23.8
	Peterson's	3,730	....	22.6	16.6	23.6	19.3	28.1	27.9	32.5	23.6	....
	Upper Meadows	4,400	....	....	....	26.8	25.3	40.6	28.3	38.4	34.6	....
	Park Creek Ridge	4,600	....	31.6	26.7	29.9	32.6	40.3	32.6	50.1	36.0	35.0[a]
	Rainy Pass	4,780	....	33.6	25.4	31.6	28.1	35.6	28.3	41.2	35.1	....
	Dagger Lake	5,200	....	35.4	25.9	33.0	29.7	41.5	34.1	56.7	43.6	....
	Agnes Creek	5,400	....	43.8	31.1	38.3	36.0	53.0	43.4	58.2	54.6	44.8[a]
	Average		25.3	25.1	17.9	24.4	23.2	34.0	27.4	39.1	27.7	....
	Average of both basins		28.8	25.8	18.3	24.4	23.0	33.9	28.2	40.0	29.2	....

[a] 8-year average.

Fig. 2

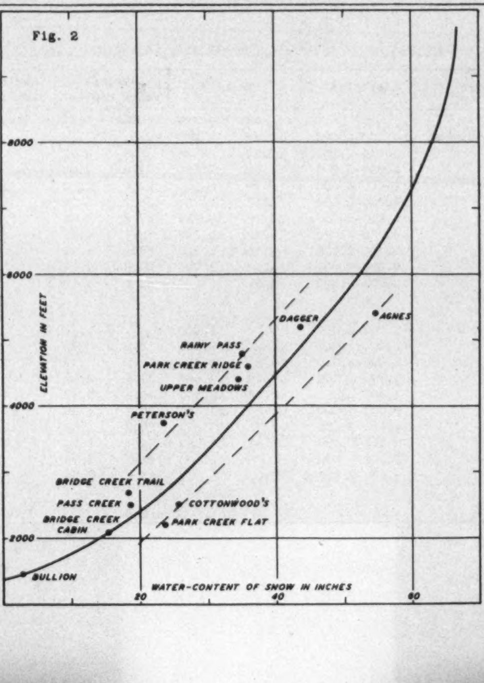


Table 3--Comparison of density in per cent, 1927-31 and 1936-39, Chelan Basin Snow-Surveys

Basin	Course	Elevation	Density of snow for year								
			1927	1928	1929	1930	1931	1936	1937	1938	1939
		feet									
Railroad Creek	Two Mile	2,020	42.3	40.3	44.3	33.0	37.7	41.4	44.1	32.9	40.3
	Seven Mile	3,015	37.0	37.2	38.5	27.8	31.0	40.9	34.8	32.7	37.8
	Greenwood	3,540	38.0	41.8	37.7	35.2	34.3	40.0	40.4	32.9	38.4
	Little Meadows	5,275	37.6	38.2	36.1	34.9	34.5	40.8	37.7	39.7	43.7
	Lyman Lake	5,900	....	36.6	36.6	34.4	34.5	39.3	38.0	41.4	44.1
	Cloudy Pass	6,500	38.3	38.0	36.6	35.2	37.5	40.7	38.8	42.8	46.0
	Average		38.6	38.7	38.3	33.4	34.9	40.5	39.0	37.1	41.7
Stehekin River	Bullion	1,460	45.6	44.2	....	46.8	46.8	41.2	43.2	43.4	41.2
	Bridge Creek	2,100	40.4	41.2	41.5	39.0	39.5	40.1	43.0	40.5	38.0
	Park Creek Flat	2,220	39.5	40.2	38.9	42.7	36.2	40.9	44.8	41.4	38.6
	Pass Creek	2,500	....	41.9	41.0	37.4	39.5	42.3	40.1	43.9	36.2
	Cottonwood	2,500	40.0	41.3	38.8	40.2	34.8	40.1	40.2	39.2	37.7
	Bridge Creek Trail	2,680	37.9	39.2	38.3	38.4	33.5	39.8	42.3	40.8	37.1
	Peterson's	3,730	....	36.8	35.3	39.6	35.6	37.6	44.2	40.8	36.8
	Upper Meadows	4,400	....	....	....	35.9	34.8	36.0	34.8	35.7	39.9
	Park Creek Ridge	4,600	....	35.5	32.9	39.0	30.9	35.4	38.9	38.0	40.7
	Rainy Pass	4,780	....	33.6	32.2	37.6	31.1	36.4	34.8	37.4	39.6
	Dagger Lake	5,200	....	35.4	33.3	39.2	31.8	37.4	37.6	45.3	42.0
	Agnes Creek	5,400	....	43.2	34.2	34.5	35.8	35.8	37.3	40.0	43.4
	Average		40.8	39.5	33.3	39.2	35.9	38.6	40.1	40.5	39.3

Table 4--Computation of water in snow-storage, Chelan Basin Snow-Surveys

Basin	Elevation	Area		Average water-content		Water in snow-storage
	feet	sq. mi.	acres	inches	feet	ac.-ft.
Railroad Creek	1,100-2,000	0.88	563	....	....	....
	(1,700-2,000)	(0.29)	(186)	2.5	0.21	39
	2,000-3,000	4.42	2,830	11.2	0.93	2,632
	3,000-4,000	9.19	5,880	24.0	2.00	11,760
	4,000-5,000	9.63	6,200	36.2	3.02	18,724
	5,000-6,000	14.43	9,240	47.2	3.93	36,313
	6,000-7,000	15.69	10,040	53.8	4.48	44,979
	7,000-8,000	8.15	5,220	58.0	4.83	25,213
	8,000-9,000	1.50	960	60.8	5.07	4,867
	9,000-9,500	0.09	58	62.2	5.18	300
			Total			144,827
Stehekin River	1,100-2,000	9.36	5,990	....	....	.....
	(1,400-2,000)	(6.24)	3,994	8.8	0.73	2,916
	2,000-3,000	24.21	15,490	21.5	1.79	27,727
	3,000-4,000	46.18	29,560	31.5	2.62	77,447
	4,000-5,000	66.88	42,800	40.4	3.37	144,236
	5,000-6,000	94.28	60,340	48.7	4.06	244,980
	6,000-7,000	94.62	60,560	55.7	4.64	280,998
	7,000-8,000	32.53	20,820	61.1	5.09	105,974
	8,000-9,000	2.75	1,760	64.8	5.40	9,504
	9,000-9,300	0.12	77	66.2	5.52	425
			Total			894,207
			Total both basins			1,039,034

Table 5--Lake Chelan inflow

	acre-feet
Railroad Creek (snow)	144,827
Stehekin River (snow)	894,207
Total snow	1,039,000
April 1 to November 1, rainfall[a]	19,000
Total	1,058,000
Unmeasured inflow[b]	198,000
Total Lake Chelan inflow	1,256,000
	or 633,000 second-feet days

[a] Based on eight years' records, 1927-31 and 1936-38; snow-survey forecast is 98.2 per cent of measured inflow.

[b] Based on 12 years' records, 1927-38; measured inflow is 84.3 per cent of total inflow.

Table 6--Lake inflow and outflow by periods, April 1 to November 1, Chelan Basin Snow-Surveys

Period	Inflow[a]		Outflow,[b] power-house	Waste	Net inflow	Equivalent Lake-height[c]
	o/o total	sfd	sfd	sfd	sfd	feet
Apr 1 - May 1	11.5	72,800	23,220	0	49,580	1084.52
May 1 - May 11	6.4	40,500	7,740	0	32,760	1087.62
May 11 - May 21	9.6	60,770	8,160	0	52,610	1089.67
May 21 - Jun 1	10.6	67,100	9,438	0	57,662	1092.95
Jun 1 - Jun 11	10.5	66,470	9,380	41,090	16,000	1096.55
Jun 11 - Jun 21	9.6	60,770	9,380	28,190	23,200	1097.55
Jun 21 - Jul 1	8.8	55,700	9,380	30,320	16,000	1099.00
Jul 1 - Jul 11	6.9	43,680	21,000	22,680	0	1100.00
Jul 11 - Jul 21	5.4	34,180	21,000	13,180	0	1100.00
Jul 21 - Aug 1	4.6	29,120	23,100	6,020	0	1100.00
Aug 1 - Aug 11	3.0	18,990	21,000	0	-2,010	1100.00
Aug 11 - Aug 21	2.3	14,560	21,000	0	-6,440	1099.87
Aug.21 - Sep 1	2.1	13,290	23,100	0	-9,810	1099.47
Sep 1 - Oct 1	4.1	25,950	63,000	0	-37,050	1098.86
Oct 1 - Nov 1	4.6	29,120	65,100	0	-35,980	1096.55
Nov 1						1094.30
Totals	100.0	633,000	......	141,480	= 8.8 feet Lake Chelan storage	

[a] Based on 22 years' records.

[b] Flow through power-house assumed at: 774 cfs for April 1 to May 15 [774 cfs = 19,850-kw output (2 machines)]; 858 cfs for May 16 to May 31 [858 cfs = 22,500-kw output (2 machines)]; 938 cfs for June [938 cfs = 25,000-kw output (2 machines)]; 2,100 cfs for July 1 to November 1 [2,100 cfs = 55,000-kw output (2 machines)].

[c] At first date of period.

Summary--Lake Chelan Basin Snow-Surveys: Water held in snow-storage was as follows on April 1 of the year indicated.

1939 = 524,800 sfd
1938 = 609,300 sfd
1937 = 428,000 sfd
1936 = 527,400 sfd
1931 = 365,700 sfd
1930 = 396,200 sfd
1929 = 317,000 sfd
1928 = 430,300 sfd
1927 = 523,100 sfd
9-year average = 457,980 sfd

Water held in snow-storage on April 1, 1939, is 14.6 per cent more than the nine-year average shown above.

Results of the snow-survey, based on snow-storage and average runoff-rates show Lake Chelan will reach elevation 1096.55 about June 1 (see p. 985). Draft from Lake Cnelan storage will commence about August 1.

During June 1 to August 1 the computations show that we will waste 141,480 sfd, which is equivalent to 8.8 feet of Lake Chelan storage. Last year our forecast waste, which was 3.5 per cent more than the actual waste, was twice the amount predicted for this year.

[Note--Graph of forecast and actual rise of Lake Chelan is given on page 985 under Forecast accuracy of water-supply as made from snow-surveys: Regional reports for the northern watersheds (2).]

SNOW-SURVEYING IN THE CASCADES: A FILM

R. A. Work

This film, shown during the luncheon of June 19, 1940, at the Hotel Edmond Meany, depicted life in shelter-huts deep beneath the snow-cover with entrance through "silo-towers" or "Santa Claus chimneys."

Soil Conservation Service,
Medford, Oregon

FORECASTING -- Continued

THE MOUNTAIN SNOW-SURVEY: ITS GENESIS, EXODUS, AND REVELATION

J. Cecil Alter

In reviewing the early beginnings of mountain snow-surveying and enumerating some of its benefits, I desire at the same time to present for your consideration a proposal for certain major changes, believed to be improvements, in the basic principles of mountain snow-surveying.

As the thirtieth annual surveys have now been reported, it may be high time we were examining the system with a view to testing what might be termed revolutionary innovations.

As the results of the snow-survey alone often bear no very definite, dependable, statistical relationships to subsequent stream-discharge data, there may be justification for proposing a material change.

And as the original mountain snow-surveys for Utah irrigators were conceived and made by me and my identification with the subsequent history of snow-surveying has been fairly active and intimate, I trust a suggestion of this kind may not seem presumptuous.

Genesis

There is reason to believe that this suggestion may place the effectiveness of all snow-survey labor and expenditure as far ahead of the present snow-survey system as the snow-survey system was in advance of the fireside estimates, or sheer guesses, that were being published by the Weather Bureau when I entered the service. That, in fact, was the reason for my suggesting to Utah's State Engineer, Caleb Tanner, in the spring of 1907, that actual measurements of the mountain snow be made.

Subsequent representations won the support of Weather Bureau officials, including A. H. Thiessen, in charge of the Salt Lake City Office, Dr. H. C. Frankenfield, in charge of the River and Flood Division, and Professor Charles F. Marvin, Chief of the Instrument Division and later Chief of Bureau.

A general plan was finally perfected, and Maple Creek Watershed was selected for the initial surveys. Maple Creek's ten square miles furnished water to irrigate five square miles of rich fruit- and farm-lands in Utah County. The first snow-survey, made at the end of March, 1911, consisted of about 2,000 exploratory depth-measurements, and 277 actual samplings in carefully selected places, with the Marvin snow-density tube and weighing scales. The results of that first survey indicated that water in the form of snow lying on two-thirds of the watershed would spread 14 inches deep over all the land reached by it. Similarly intensive surveys were made on the Maple Creek proving ground in 1912 and 1913, the conclusion becoming obvious that one-tenth as many soundings would give equally good results.

Exodus

Then came the Exodus, or "the going out," of the snow-survey to other lands and into other hands. Descriptive, educational articles setting forth the theory, plan, and working details of those surveys were published as special bulletins, in the reports of climatological data, and in the Year Book of the Department of Agriculture for 1911, crude though the instruments and methods were, compared to the refinements introduced in recent years by professional snow-surveyors.

The Scientific American Supplement for June 29, 1912, carried a feature story summarizing the first two annual snow-surveys, which was picked up by many other periodicals--five or six of them in foreign lands and in foreign languages. Popular, illustrated articles were further broadcast after the third survey in 1913 by newspaper syndicates "The Independent," "Irrigation Age," "Engineering News," and other publications.

The United States Bureau of Reclamation introduced snow-surveys on most of the watersheds above its reservoirs in the west, several irrigation-companies sent snow-surveyors into the mountains, and municipalities such as Logan and Salt Lake City, Utah, dependent for water-supplies on mountain snow, took an active and lasting interest through their engineering and water-works departments. Very quickly, however, the snow-survey activity of the Salt Lake Office of the Weather Bureau outran our facilities to handle and our authority to continue the work. More men and more money were needed than could be allotted for the purpose. The snow-survey thus rather abruptly became a country-wide activity, and no longer belonged to a single agency.

Through an article published two years later, April 17, 1915, in the "Engineering Record," we first learned that Dr. J. E. Church, Jr., of Reno, had been making experimental snow-measurements on Mount Rose, Nevada, since 1909.

Then in the "Journal of the New England Water Works Association" [v. 33, No. 1, 1919] we were to learn from Robert E. Horton that "among the earliest records of accumulated snow and its water-equivalent in the United States, were those kept by Charles A. Mixer, at Rumford Falls, Maine, in 1901 to 1903, and by the writer (Horton) at Utica, New York, in 1903 and 1904. Apparatus for snow-sampling and weighing developed at Utica formed a pattern for subsequent improved apparatus of the United States Weather Bureau." Mr. Horton added the opinion that it was an easy matter to keep a record, say once a week, of the water-equivalent of accumulated snow on the ground, checked by an ordinary record of precipitation. Incidentally, the Horton snow-tube was 5.94 inches in diameter, made in two sections of two feet and three feet each, fitted with an auger or cutter for lifting the snow-sample.

A recent review of Dr. Church's original reports reveals the character and importance of his early snow-work. In the 1909 report of the Department of Meteorology and Climatology to the Director of the Nevada Agricultural Experiment Station, Dr. Church describes the snow-density tube and scales which he and his assistants had developed that year. These were developed for use in his primary study of the relationship of forests to snow-conservation.

Dr. Church was thus encouraged to remark "By carefully determining the snow-content of the various districts of the watershed, ... knowledge of the runoff can be acquired so as to predict the result of the (Tahoe) Lake level within close limits. ..... In this way the cause of agriculture under irrigation can be materially advanced." A very significant prophecy indeed!

In 1910, the snow-sampler, weighing scales, and experimental sampling-methods were materially improved, leading Dr. Church to report with more assurance "The way is now opened to determine with exactness the water-equivalent of the snow on the ground in the highest mountains at the beginning of the season of melting."

In 1911, Dr. Church proposed "The reinauguration and extension of snow-measurements around Lake Tahoe for the purpose of ultimately making forecasts of floods, and water available for irrigation," having that year actually made an estimate of the supply.

Accordingly, additional snow-courses were established in 1912. In the spring of 1913, the Truckee River General Electric Company, and the United States Reclamation Service, cooperated in snow-surveys affecting their interests, and the Electric Company's hydrographer, L. O. Murphy, predicted the level of Lake Tahoe "within one-tenth of a foot of the level actually attained."

According to a recapitulation or retrospective view in the report for 1914, the annual snow-measurements, in the Lake Tahoe Basin, comparable as to time and place, were begun simultaneously with those on Maple Creek Watershed, Utah. And I am sure Dr. Church knew no more of our work in Utah at the time, than we knew of his!

In Utah the snow-surveys saw their greatest development under the energetic and skilful work of George D. Clyde, now Dean of the School of Engineering, Utah State Agricultural College, at Logan. Beginning in 1923, Dean Clyde, through several years of intensive work, forced the Utah system to its apex of usefulness.

The greatest expansion of the general snow-surveys throughout the west has of course been fostered in recent years by the Division of Irrigation of the United States Bureau of Agricultural Engineering, and later by the Soil Conservation Service, a phase of history not comprehended in this review.

Leviticus

The Snow-survey system forms a correct measure or appraisal of the available moisture existing at the moment, in the form of snow, and to a certain extent it may be an index of the general water-supply. But specifically, it is merely an inventory of the water-user's assets then reposing in the snow-banks, like the actual "cash-on-hand" item in a bank statement.

However, it is far from a complete statement of the entire assets of the repository. For, as a "cash-on-hand" statement says nothing about stocks, mortgages, bonds, and other investments and securities, neither does the spring snow-survey necessarily bear any fixed relation to the amount of precipitation upon the watershed previous to the snow-survey, or to the amount of water that may flow down the stream-channel.

In occasional mild winters or warm early springs, a low-level snow-course may be bare at snow-survey time. But that zero-index does not necessarily dry up the stream; for the watershed-subsoils may be saturated as a result of previous wet weather.

Wherever and whenever the snow-survey figures represent less than half of the seasonal precipitation to date, their predictive value in anticipating stream-discharge is much less dependable. If the snow-course is at a moderately high altitude, and the winter has been stormy, cold, and prolonged--so that the spring snow-survey figures represent as much as 80 per cent or 90 per cent of the total seasonal precipitation-deposits--obviously they will have a comparatively high predictive or correlating value.

For that reason the connection must be established between the snow-survey and the previous precipitation-history. Only precipitation-gages, properly located and attended, are needed to provide this necessary adequate record. The snow-surveyors' methods and devices provide an accurate sample of the snow-layer on the ground; but so does the precipitation-gage take an equally accurate sample of all the precipitation originally reaching the ground. There is this difference however: The operation of a precipitation-gage calls for a minimum of human effort, and it works while we sleep! Moreover, the usefulness of a precipitation-record is cumulative and often gives an inkling, some months in advance, of the status of the water-supply.

As precipitation-measurement provides a record of the moisture deposited on the watershed, so does a stream-gaging record show the moisture expended, being in fact a measure of the effective precipitation. Thus these two companion items, precipitation and stream-gagings, are inseparable in seasonal stream-forecasting.

If we have a snow-survey course or a precipitation-station that is not paired with a stream-gaging station, how are we to determine its ultimate accuracy or usefulness? Also without a stream-gaging record how are the hold-over effects of a previous drouth or a deluge to be studied, analyzed, and anticipated?

The constant depletion through evaporation, subterranean diversion, and otherwise in unmeasured but varying quantities of the precipitation received, as well as the impracticability of computing the precise area of mountain surface occupied by the snow- or precipitation-layer, often renders very difficult the direct computation of the precipitation-stream-flow relationship.

Consequently, the unit-areas per precipitation-gage and per stream-gaging station must be made as small as practicable, that is, there must be as many stream and precipitation gaging-stations as practicable to raise the correlation to its highest efficiency. Precipitation-stations poorly distributed, or insufficient in numbers, are like snow-courses improperly placed--they do not always form good indexes to the water-supply of the region.

Usually wherever a snow-course is needed, a precipitation-gage is needed in its vicinity. However, the atmospheric conditions, that result in precipitation, are usually rather wide-spread or are of similar character on fairly large areas, so that a precipitation-gage may be located entirely off the watershed and yet be an indicator of precipitation on the watershed and of the seasonal discharge of the stream that drains it.

Revelation

Now in a closing chapter, let us look at some parallel snow-survey, precipitation, and stream-flow records carefully and continually kept on the same watershed. The longest of these, running concurrently, so far as known, appear to be those on Big Cottonwood Creek, near Salt Lake City, which have now continued 21 years.

Big Cottonwood Watershed comprises about 50 square miles and has an average annual yield of 50,000 or 60,000 acre-feet. Little Cottonwood Creek, adjacent to the south, is about 60 per cent of Big Cottonwood in size and in volume of discharge; while the four smaller streams immediately to the north drain a combined area of about 100 square miles and together contribute about 75 per cent as much water as Big Cottonwood.

Silver Lake, in the headwater-basin of Big Cottonwood Creek (elevation 8,725 feet) gets about 30 feet of snow in an average winter and has had 40 feet. Accumulated snow-depths are often seven feet and have exceeded ten feet. The average annual precipitation is 43 inches, or nearly three times that in the adjacent Salt Lake Valley.

The standard snow-course at Silver Lake consists of 26 measuring sites, 50 feet apart. It is located on level ground, only a few rods from the daily precipitation-measurement station. All observations are made by standard methods and standard equipment.

The total seasonal stream-discharge for April to July (beginning at the date of the snow-survey and ending after the high-water has subsided) has been used in this comparison (see Table 1). It has been prepared in four columns for (a) Big Cottonwood, (b) Little Cottonwood, (c) Big and Little Cottonwood combined, and (d) for all six streams combined. These four sets of figures usually bear some relationship to one another but not always--as any hydrographer would understand.

The snow-survey depth and water-content values on March 31, also the seasonal precipitation-totals for the six snow-storage months ending with the March 31 snow-survey, are likewise compiled for comparison.

The precipitation-records at eight stations in the vicinity have been used--four of them off the watersheds to the west, two stations being on the watersheds, and two stations being located 6 to 12 miles beyond the watershed to the southeast. Records at a total of ten precipitation-stations, or groups of stations, have thus been compared with the snow-survey and with the stream-discharge values, all data being shown each year in percentage of the 21-year mean. This gives in all about 50 slightly different indicators, or combinations of indicators, all of which supposedly point to the prospective water-supply or seasonal discharge in one or more of the streams.

Singularly enough, both the snow-depth and water-content values at Silver Lake, when compared with the subsequent stream-discharges, showed an average miss of about 18 per cent. However, both sets of predicting figures had a few bulls-eye hits and several that missed less than ten per cent.

When corrected for excessive and deficient precipitation occurring after the snow-survey, during the period of runoff, that is, when adjusted to a normal precipitation during the runoff-months, the average deviation was only 15.6 per cent.

This "corrected" variation of 15.6 per cent results in a large measure from variations in the evaporation and other "constants," which are not constant but are constantly varying. (You see it calls for more evaporation-measurement stations--but that is another story!)

Table 1--Comparison of precipitation and snow-survey values with subsequent stream-discharge in the Salt Lake City Area (all values in percentages of 21-year average)

Year	Stream-discharge				March 31 snow-depth Silver Lake				
	April to July			April to September, all streams					
	Big Cotton-wood (a)	Little Cotton-wood (b)	Big and Little Cottonwood (c)	(d)		(a)	(b)	(c)	(d)
1919	91	73	82	83	90	-1	+17	+8	+7
1920	137	91	114	118	128	-9	+37	+14	+10
1921	181	159	170	184	135	-46	-24	-35	-49
1922	154	123	138	160	155	+1	+32	+17	-5
1923	139	117	128	134	114	-25	-3	-14	-20
1924	74	62	68	65	111	+37	+49	+43	+46
1925	102	97	99	96	78	-24	-19	-21	-18
1926	87	85	86	82	79	-8	-6	-7	-3
1927	124	147	135	129	111	-13	-36	-24	-18
1928	98	110	104	103	80	-18	-30	-24	-23
1929	115	120	117	125	98	-17	-22	-19	-27
1930	71	77	74	69	90	+19	+13	+16	+21
1931	50	56	53	48	53	+3	-3	0	+5
1932	107	119	113	109	123	+16	+4	+10	+14
1933	97	79	88	88	88	-9	+9	0	0
1934	31	44	37	32	63	+32	+19	+26	+31
1935	83	96	94	82	78	-5	-18	-16	-4
1936	103	106	104	110	137	+34	+31	+33	+27
1937	83	97	90	93	108	+25	+11	+18	+15
1938	104	136	120	113	108	+4	-28	-12	-5
1939	69	106	86	77	73	+4	-33	-13	-4
			Means			16.7	21.1	17.6	16.8
			4-column mean				18.0		

Year	March 31 snow-survey Silver Lake					March 31 snow-survey corrected					Corrected precipitation Silver Lake				
		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)
1919	72	-19	-1	-10	-11	70	-21	-3	-12	-13	94	+3	+21	+12	+11
1920	85	-52	-6	-29	-33	93	-44	+2	-21	-25	117	-20	+26	+3	-1
1921	100	-81	-59	-70	-84	110	-71	-49	-60	-74	143	-38	-16	-27	-41
1922	147	-7	+24	+9	-13	156	+2	+33	+18	-4	148	-6	+25	+10	-12
1923	128	-11	+11	0	-6	135	-4	+18	+7	+1	122	-17	+5	-6	-12
1924	84	+10	+22	+16	+19	76	+2	+14	+8	+11	76	+2	+14	+8	+11
1925	92	-10	-5	-7	-4	93	-9	-4	-6	-3	91	-11	-6	-8	-5
1926	75	-12	-10	-11	-7	77	-10	-8	-9	-5	70	-17	-15	-16	-12
1927	130	+6	-17	-5	+1	137	+13	-10	+2	+8	120	-4	-27	-15	-9
1928	98	0	-12	-6	-5	95	-3	-15	-9	-8	90	-8	-20	-14	-13
1929	108	-7	-12	-9	-17	113	-2	-7	-4	-12	103	-12	-17	-14	-22
1930	95	+24	+18	+21	+26	92	+21	+15	+18	+23	71	0	-6	-3	+2
1931	38	-12	-18	-15	-10	34	-16	-22	-19	-14	50	0	-6	-3	+2
1932	128	+21	+9	+15	+19	122	+15	+3	+9	+13	116	+9	-3	+3	+7
1933	106	+9	+27	+18	+18	112	+15	+33	+24	+24	105	+8	+26	+17	+17
1934	70	+39	+26	+33	+38	48	+17	+4	+11	+16	51	+20	+7	+14	+19
1935	89	+6	-7	-5	+7	97	+14	+1	+3	+15	98	+15	+2	+4	+16
1936	150	+47	+44	+46	+40	142	+39	+36	+38	+32	129	+26	+23	+25	+19
1937	105	+22	+8	+15	+12	104	+21	+7	+14	+11	102	+19	+5	+12	+9
1938	113	+9	-23	-7	0	119	+15	-17	-1	+6	124	+20	-12	+4	+11
1939	87	+18	-19	+1	+10	75	+6	-31	-11	-2	80	+11	-26	-6	+3
Means	...	20.1	18.0	16.6	18.1	...	17.1	15.8	14.5	15.2	...	12.7	14.7	10.7	12.1
4-column mean			18.2					15.6					12.5		

Table 1--Comparison of precipitation and snow-survey values with subsequent stream-discharge in the Salt Lake City Area (all values in percentages of 21-year average)--Continued

Year	Precipitation from October to March														
	Salt Lake					Cottonwood Weir					Silver Lake				
		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)
1919	69	-22	-4	-13	-14	75	-16	+2	-7	-8	96	+5	+23	+14	+13
1920	124	-13	+33	+10	+6	120	-17	+29	+6	+2	109	-28	+18	-5	-9
1921	118	-63	-41	-52	-66	131	-50	-28	-39	-53	133	-48	-26	-37	-51
1922	123	-31	0	-15	-37	122	-32	-1	-16	-38	139	-15	+16	+1	-21
1923	123	-16	+6	-5	-11	125	-14	+8	-3	-9	115	-24	-2	-13	-19
1924	87	+13	+25	+19	+22	86	+12	+24	+18	+21	84	+10	+22	+16	+19
1925	122	+20	+25	+23	+26	117	+15	+20	+18	+21	90	-12	-7	-9	-6
1926	82	-5	-3	-4	0	80	-7	-5	-6	-2	68	-19	-17	-18	-14
1927	113	-11	-34	-22	-16	107	-17	-40	-28	-22	113	-11	-34	-22	-16
1928	110	+12	0	+6	+7	93	-5	-17	-11	-10	93	-5	-17	-11	-10
1929	103	-12	-17	-14	-22	107	-8	-13	-10	-18	98	-17	-22	-19	-27
1930	66	-5	-11	-8	-3	62	-9	-15	-12	-7	74	+3	-3	0	+5
1931	62	+12	+6	+9	+14	76	+26	+20	+23	+28	54	+4	-2	+1	+6
1932	87	-20	-32	-26	-22	97	-10	-22	-16	-12	122	+15	+3	+9	+13
1933	92	-5	+13	+4	+4	86	-11	+7	-2	-2	99	+2	+20	+11	+11
1934	68	+37	+24	+31	+36	75	+44	+31	+38	+43	73	+42	+29	+36	+41
1935	98	+15	+2	+4	+16	93	+10	-3	-1	+11	90	+7	-6	-4	+8
1936	113	+10	+7	+9	+3	102	-1	-4	-2	-8	137	+34	+31	+33	+27
1937	111	+28	+14	+21	+18	103	+20	+6	+13	+10	103	+20	+6	+13	+10
1938	120	+16	-16	0	+7	137	+33	+1	+17	+24	118	+14	-18	-2	+5
1939	109	+40	+3	+23	+32	106	+37	0	+20	+29	92	+23	-14	+6	+15
Means	...	19.3	15.0	15.1	18.2	...	18.8	14.1	14.6	18.0	...	17.0	16.0	13.3	16.5
4-column mean			16.9					16.4					15.7		

Year	Salt Lake, Cottonwood Weir					Salt Lake, Silver Lake, Cottonwood Weir					5-station mean[a]				
		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)
1919	72	-19	-1	-10	-11	80	-11	+7	-2	-3	88	-3	+15	+6	+5
1920	122	-15	+31	+8	+4	117	-20	+26	+3	-1	114	-23	+23	0	-4
1921	124	-57	-35	-46	-60	127	-54	-32	-43	-57	134	-47	-25	-36	-50
1922	122	-32	-1	-16	-38	128	-26	+5	-10	-32	135	-19	+12	-3	-25
1923	124	-15	+7	-4	-10	121	-18	+4	-7	-13	113	-26	-4	-15	-21
1924	86	+12	+24	+18	+21	86	+12	+24	+18	+21	81	+7	+19	+13	+16
1925	120	+18	+23	+21	+24	110	+8	+13	+11	+14	102	0	+5	+3	+6
1926	81	-6	-4	-5	-1	77	-10	-8	-9	-5	76	-11	-9	-10	-6
1927	110	-14	-37	-25	-19	111	-13	-36	-24	-18	118	-6	-29	-17	-11
1928	102	+4	-8	-2	-1	99	+1	-11	-5	-4	103	+5	-7	-1	0
1929	105	-10	-15	-12	-20	103	-12	-17	-14	-22	103	-12	-17	-14	-22
1930	64	-7	-13	-10	-5	67	-4	-10	-7	-2	68	-3	-9	-6	-1
1931	68	+18	+12	+15	+20	64	+14	+8	+11	+16	56	+6	0	+3	+8
1932	92	-15	-27	-21	-17	102	-5	-17	-11	-7	106	-1	-13	-7	-3
1933	89	-8	+10	+1	+1	92	-5	+13	+4	+4	92	-5	+13	+4	+4
1934	72	+41	+28	+35	+40	72	+41	+28	+35	+40	69	+38	+25	+32	+37
1935	96	+13	0	+2	+14	94	+11	-2	0	+12	89	+6	-7	-5	+7
1936	108	+5	+2	+4	-2	117	+14	+11	+13	+7	125	+22	+19	+21	+15
1937	107	+24	+10	+17	+14	106	+23	+9	+16	+13	109	+26	+12	+19	+16
1938	128	+24	-8	+8	+15	125	+21	-11	+5	+12	121	+17	-15	+1	+8
1939	108	+39	+2	+22	+31	102	+33	-4	+16	+25	98	+29	-8	+12	+21
Means	...	18.9	14.2	14.4	17.0	...	17.0	14.1	12.6	15.6	...	14.9	13.6	10.9	13.6
4-column mean			16.3					14.8					13.2		

[a] Midvale, Lower Mill Creek, Salt Lake City, Silver Lake, and Snake Creek.

Table 1--Comparison of precipitation and snow-survey values with subsequent stream-discharge in the Salt Lake City Area (all values in percentages of 21-year average)--Concluded

Year	Precipitation from October to March														
	8-station mean[b]					Silver Lake (once), Snake Creek (3 times), Heber (4 times)					Salt Lake (once), Silver Lake (once), Cottonwood Weir (twice), Snake Creek (5 times), Heber (6 times)				
		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)		(a)	(b)	(c)	(d)
1919	87	-4	+14	+5	+4	95	+4	+22	+13	+12	91	0	+18	+9	+8
1920	113	-24	+22	-1	-5	106	-31	+15	-8	-12	108	-29	+17	-6	-10
1921	133	-48	-26	-37	-51	151	-30	-8	-19	-33	148	-33	-11	-22	-36
1922	128	-26	+5	-10	-32	137	-17	+14	-1	-23	134	-20	+11	-4	-26
1923	110	-29	-7	-18	-24	104	-35	-13	-24	-30	107	-32	-10	-21	-27
1924	79	+5	+17	+11	+14	67	-7	+5	-1	+2	68	-6	+6	0	+3
1925	100	-2	+3	+1	+4	82	-20	-15	-17	-14	87	-15	-10	-12	-9
1926	79	-8	-6	-7	-3	81	-6	-4	-5	-1	82	-5	-3	-4	0
1927	116	-8	-31	-19	-13	133	+9	-14	-2	+4	131	+7	-16	-4	+2
1928	106	+8	-4	+2	+3	104	+6	-6	0	+1	104	+6	-6	0	+1
1929	104	-11	-16	-13	-21	98	-17	-22	-19	-27	100	-15	-20	-17	-25
1930	67	-4	-10	-7	-2	67	-4	-10	-7	-2	66	-5	-11	-8	-3
1931	60	+10	+4	+7	+12	49	-1	-7	-4	+1	52	+2	-4	-1	+4
1932	107	0	-12	-6	-2	120	+13	+1	+7	+11	116	+9	-3	+3	+7
1933	89	-8	+10	+1	+1	90	-7	+11	+2	+2	89	-8	+10	+1	+1
1934	68	+37	+24	+31	+36	72	+41	+28	+35	+40	72	+41	+28	+35	+40
1935	90	+7	-6	-4	+8	80	-3	-16	-14	-2	82	-1	-14	-12	0
1936	123	+20	+17	+19	+13	128	+25	+22	+24	+18	124	+21	+18	+20	+14
1937	112	+29	+15	+22	+19	112	+29	+15	+22	+19	111	+28	+14	+21	+18
1938	126	+22	-10	+6	+13	123	+19	-13	+3	+10	125	+21	-11	+5	+12
1939	103	+34	-3	+17	+26	101	+32	-5	+15	+24	103	+34	-3	+17	+26
Means	...	16.4	12.5	11.6	14.6	...	17.0	12.7	11.5	13.7	...	16.1	11.6	10.6	13.0
4-column mean		13.8					13.7					12.8			

[b] Midvale, Lower Mill Creek, Mt. Dell Dam, Salt Lake City, Silver Lake, Cottonwood Weir, Snake Creek, and Heber.

Now here is the final point in this paper: The Salt Lake City precipitation-record, made 25 miles to the northwest of Silver Lake Basin and ten miles from the nearest edge of the watersheds, when used as a forecasting figure, shows an average error of 17 per cent, or one per cent better than the snow-survey figures. The Cottonwood Wier precipitation-record, 12 miles southeast of Salt Lake City at the mouth of Big Cottonwood Canyon, rates 16.5 per cent; while Silver Lake is still better, or 15.7 per cent. That is, if the Silver Lake precipitation-record had been used, instead of the Silver Lake snow-survey figures, to predict the seasonal runoff, the average miss for 21 years would have been 15.7 per cent instead of 18.2 per cent.

For the flow of Big Cottonwood Creek alone, the figures are 17.0 per cent for precipitation and 20.1 per cent for snow-survey. For Big and Little Cottonwood combined, the percentages are 13.3 per cent for precipitation and 16.6 per cent for snow-survey, or more than three per cent in favor of precipitation.

A still greater improvement would have been made by using all three of these precipitation-stations combined, in which case the average forecast-error was only 14.8 per cent. On the two larger creeks combined, the efficiency-ratio was 12.6 per cent for precipitation and 16.6 per cent for snow-survey--an improvement of four per cent.

By using the mean values for five precipitation-stations--though four of them are entirely off the watersheds--the general forecasts for stream-flow would have averaged only 13.2 per cent from the actual (as compared with error of 18 per cent by using the snow-survey values). The combined discharge of Big and Little Cottonwood creeks is predicted by the Silver Lake snow-survey with an average miss of 16.6 per cent; whereas the prediction, using the means of the five-precipitation-station group, misses an average of only 10.9 per cent--a gain of nearly six per cent. Thus in four out of five years, better predictions are indicated with precipitation than with snow-surveys.

Now you and I know that these comparisons will not be the same on all watersheds; nor will they be exactly the same on these particular watersheds during the next 21 years. But they are believed to point, with unerring aim, toward a better method of snow-surveying for the future!

A number of hydrologists, for some time on other watersheds, have been using precipitation-data exclusively in their stream-forecasting. The above comparative figures may explain one reason why!

More precipitation-records

When snow-surveys were first proposed, precipitation-stations were comparatively scarce. The Weather Bureau was then publishing precipitation-data for 60 or 70 stations in Utah, as compared to twice that number today. And while the average length and relative usefulness of the precipitation-records was then about ten years, the average is more than 30 years in length today.

As indicated in the beginning of this paper, mountain snow-reporting used to be a fireside guessing affair; but in recent years it has developed into a comparatively strenuous exacting chore. But if precipitation-records should ultimately take the place of any snow-survey course for predicting stream-discharge, the job would again rate as an indoor or fireside occupation, yet having all the accuracy of measurements and efficiency of results that characterize the measurements of the rest of the hydro-meteorological cycle, of which it is a major part!

U. S. Weather Bureau,
Salt Lake City, Utah

DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--I am glad indeed to concur with Mr. Alter that each of us knew nothing of the work of the other in the days of its inception. Nor did either of us know until long after concerning the pioneer work in America of Mixer and Horton. Even yet only the vaguest knowledge has come from Europe regarding snow-weighing there.

It is genuinely characteristic of Americans, especially when young and enthusiastic, to attempt the "new" before determining the old. There is at least the zest of "discovery." I have often wondered in later years whether there was really only one Adam, or first man, or a half-dozen spontaneous creations in various parts of the world. So actually with snow-surveyors. The times bore them.

The snow-sampler by Horton merely had a sharpened end drawn out smaller in diameter than the remainder of the tube. The United States Weather Bureau for a time abandoned snow-tubes because it felt that tubes could not be driven through the snow-cover successfully. Dr. Marvin, later designer of the Marvin snow-weighing tube, inquired regarding the reason for the success of the Mount Rose sampler and was given the enigmatical answer that it was "all in the point." However, additional improvement was still necessary to prevent occasional adhesion.

The first forecast on Mount Rose was based on snow-surveys made in the spring of 1910 and 1911. Being based upon the relative or percentage method, the data were few and the forecast brief. It read as follows: "On Mount Rose the amount of moisture in the form of snow available for irrigation the present season was 44.4 inches, or almost double the amount (23.5 inches) available last season. Furthermore, on account of the lateness of the spring, 38.3 inches of moisture were available as late as June, whereas only 7.2 inches were available a year ago" [Ann. Rep., Nevada Agric. Exp. Sta., June 30, 1911].

The "Revelation" that precipitation-measurements are slightly more accurate in the same watershed than snow-surveys, and considerably more so at a distance from the watershed, is based on statistical analysis rather than upon the principles of meteorology and hydrology.

In the first place, discord frequently exists between precipitation at high and low altitudes, though adjacent. In the second place, the precipitation at lower altitudes may occasionally fall as rain instead of snow or the snow-cover here may melt prematurely and run off before the season of measured flow. The snow-residue must then represent the succeeding runoff far better than vanished moisture.

The use of snow-depth measurements varies little from those of water-content, for the reason that density is fairly uniform year by year at date of melting as shown in the Report for Chelan

Basin for 1939 [see pp. 887-892], providing there has been no recent fall of new snow. Hence their inclusion in the comparison affords an opportunity to determine the value of snow-depth only, which requires merely a yard-stick for taking.

The uniformity of snow-cover or precipitation over large areas was first demonstrated by the following comparison of the snow-cover of the self-same regions compared by Mr. Alter:

"The results of three years' measurements made by the Engineering Department of Salt Lake City and the United States Weather Bureau in the Wasatch Range of Utah, whence the water-supply of Salt Lake City is obtained, indicate conclusively that estimates based on a careful survey in one of the basins can be applied with very slight error to another basin within 14 miles and probably also to basins much farther distant.

"The maximum variation on the basis of seasonal percentage between the runoff of the two streams measured, namely, Big Cottonwood Canyon and City Canyon creeks for the three years, 1913-16, was only 4.3 per cent and the maximum variation between the estimates of the snow in the two basins was 7.1 per cent. However, the maximum difference between the estimates and the runoff was as great as 16.7 per cent. The details are presented in Table 1.

Table 1--Variation negligible between near basins in Wasatch Range in respect to forecasting runoff

Variation between snow-cover and runoff in Big Cottonwood and City Creek canyons (total distance 14 miles)	1913-1914	1914-1915	1915-1916
	per cent	per cent	per cent
Using average of joint estimates in forecasting average of joint runoff........................	-11.5	-0.3	+11.8
Using estimate in one basin to forecast runoff in the other			
(1) In Big Cottonwood Canyon for City Canyon..........	- 9.9	-2.5	+12.4
(2) In City Canyon for Big Cottonwood Canyon........	-13.2	+1.9	+11.3
Maximum variation.......	1.7	2.2	1.1

"The gain from using both basins for purposes of estimating the runoff seems ordinarily too slight to justify the maintenance of a seasonal snow-survey in both." [Unpublished monograph "Snow-surveying in relation to forecasting streamflow" by J. E. Church.]

The comparison was inspired by the laborious attempt of the City Engineers of Salt Lake City to make quantitative snow-surveys in precipitous Big Cottonwood Canyon and the omission of an inaccessible portion of the area from the snow-survey estimates. This comparison was then applied with startling success to areas in the Sierra Nevada for distances of 90 miles, and the Nevada or percentage system of forecasting attained immediate maturity.

I wonder whether the close accuracy between the precipitation-stations at Salt Lake City and Cottonwood Weir is a climatic continuation of the similarity between City Canyon Creek and Big Cottonwood Creek basins found to exist in 1913-16. Silver Lake deserves physical investigation for peculiarity of situation or topography. The comparison of data by percentages reduces all stations to a common standard. Could not each year now be carefully analyzed in the light of variable factors? From the two decades of record, wide variations from average conditions could probably be found and resultant effects discovered.

EQUIPMENT

R. C. Farrow, Chairman

A PLAN FOR THE STUDY OF SNOW-COHESION AND SNOW-LOADS IN ESTIMATING THE NECESSARY STRENGTH OF ROOFS AGAINST SNOW-OVERLOAD

R. A. Work

The present plan is the result of the presentation of the paper by myself and Mr. Parshall at the Spokane meeting on the Construction of Snow-Survey Shelter-Cabins [Trans. Amer. Geophys. Union, 1939, pp. 125-135]. At that time I mentioned that purlins and shakes constituted the roof of our cabins and yet that a weight of 12.5 tons of snow had been measured above one of them. Our cabins are approximately 10 by 17 feet in horizontal dimensions and nearly 11 feet from ground to gable.

However, the snow in our Oregon territory has been so short the past season as to preclude the possibility of the sampling methods suggested, for rather than the customary 12 to 20 feet in the Cascades, we have depths this year ranging from two to seven feet. There is very little possibility that our shelter-cabins are completely covered, let alone to any considerable depth. We have been thinking along the lines of the paper suggested, and rather definitely plan to collaborate during the coming year with a representative of Crater Lake National Park in preparation of a paper on this subject. We have prepared an exact one-sixth scale-model of a deep-snow shelter-cabin, which we plan to use in the studies.

Soil Conservation Service,
Oregon Cooperative Snow Surveys,
Medford, Oregon

DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--My discussion of dead weight on roofs at the Spokane meeting may bear repeating now [Trans. Amer. Geophys. Union, 1939, pp. 134-135].

"Judging from the size of the rafters and the thinness of the shakes of the shelter-cabin at Seven Lakes, it seems improbable that the roof actually bore the total weight of 12.5 tons represented by the snow-cover above it. More probably, the snow-mass became sufficiently coherent before the upper strata were accumulated to carry the additional load. Such would be the case if a culvert were being covered by accumulating cement. The first pouring would support the later ones with little additional burden on the culvert beneath. Here is an interesting problem.

"This, of course, does not apply to a roof projecting above the snow. Here wreckage is caused by the transference of melt-water to the eaves where it accumulates as ice in sufficient quantity to break them down or distort the building through uneven strains."

I have never known the flat-roof cabins at Donner Pass to be broken in by the snow, although they were buried so deep beneath the continuous snow-cover that they could be found during the winter only by snow-sampling to determine their contours. However, towers have been stripped of their cross-braces and fence-posts of their boards unless the latter were shielded by heavy timbers laid on the top of the fence-posts to split the settling snow. The problem of protecting eaves as well as roofs against settling snow enters therefore into the study.

The Swiss Snow and Avalanche Commission has already done much field-work in determining the cohesion of snow and plans have been formed to purchase a copy of its movie-film for use among snow-survey and ski-groups in America.

A study should likewise be made of increase in cohesion of snow with increase in depth and age and also with such heat as may rise into the snow-cover from the underlying building. Cannot sampling at various depths provide snow-cores for tests of cohesion and compression?

Professor Boardman has suggested that the purlins may provide supports for the "snow-arches" above the shakes in the same manner as the ground provides support for the "snow-arch" over the building.

A model building could perhaps be provided with a free roof resting on a weighing device that would indicate increasing and diminishing overload with change in the character of the snow.

At least, the compression of the snow against the roof could be determined, particularly the snow's ability to upbear itself if the roof is removed. A side-tunnel could easily lead into the experimental cabin without affecting the supporting character of the snow.

IMPROVEMENTS TO THE TUCKER MOTOR-SLED TO SURMOUNT DIFFICULTIES IN TRAVERSING POWDER-SNOW

John T. Ryan

For many years man has been trying to build a self-propelled machine to carry him over snow-covered terrain, with the result that at present there are several types in more or less general use. Some use air-fan, crawler-track, revolving helix, and even wheel (as Admiral Byrd's snowmobile) to obtain motion.

The problem of the pioneers in this field was a greater one than that of experimenters of the present, inasmuch as the pioneer was confronted with the necessity of finding a practical source of power. Naturally his first efforts were with sail, steam, and animal. The last mentioned is still extensively used and is undoubtedly the most reliable, though it should properly not be regarded as self-propelled. But today, with the high development of the gasoline engine, the problem is resolved into one of power-application and method of supporting the machine on the surface of the snow, which is the principal topic of this paper.

The machines of the present may be classified under two headings, according to the manner in which they are supported on the snow-surface, namely, (1) those in which the machine is supported on runners or skis and (2) those in which the machine is supported on crawler-tracks or wheels.

Of the latter (track), all that I know of are relatively heavy and when bogged down must be released by other heavy equipment, which fact limits them to service with highly organized business projects.

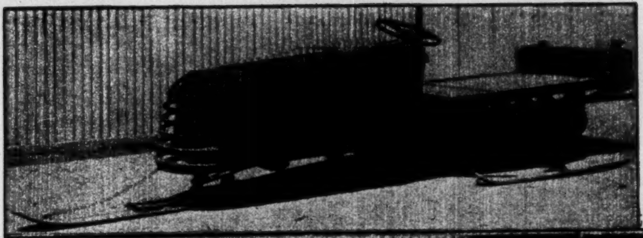
Of the former (ski), some are heavy and some are light enough to be handled manually. The light machine, to my mind, is the only type to consider in connection with snow-survey equipment. Of this type of machine two methods of obtaining motion seem to predominate, namely, (1) air-fan and (2) revolving drum with a helical thread wrapped around its surface, both powered by light gasoline engine.

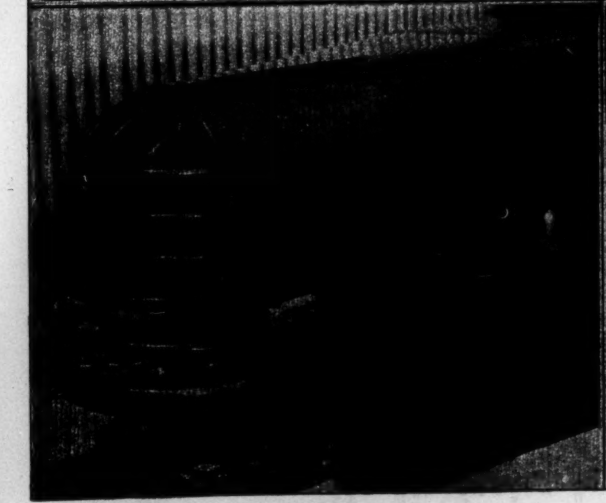
The air-fan finds its usefulness in flat unbroken country where high speed can be utilized, which fact of course eliminates it as practical for snow-surveying, leaving only the second type to be considered. This type is well illustrated by the "Tucker motor-sled" as shown in Figures 1, 2, and 3. (A moving-picture film was displayed and descriptive advertising literature was distributed.)

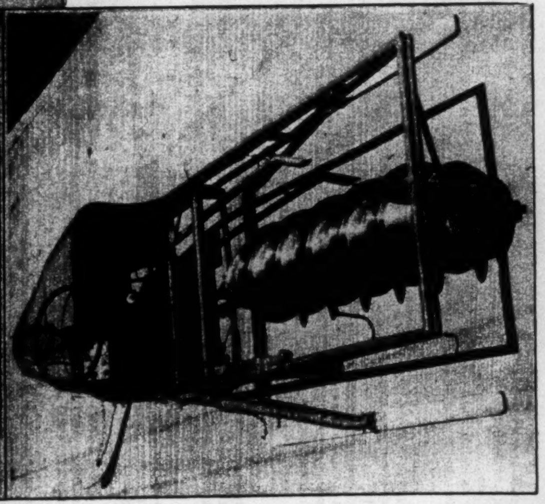
The unit weighs approximately 500 pounds with a 15-horsepower air-cooled gasoline engine, and was demonstrated to Dr. Church and others, including the writer, on the slopes of the Mount Rose region south of Reno last winter.

On one occasion a party of five left Reno by automobile pulling the sled on a trailer and traveled in about 40 minutes the 16 or 17 miles to the point where the snow-plow had stopped on the Mount Rose Road, showing that the machine is easily transported over open roads. On arriving the trailer was backed up to the snow-bank, which was some 18 inches higher than the trailer-bed, and the sled was backed off the trailer onto the snow under its own power, with some help. From here the five of us rode on the sled probably four miles up the road, the grade being about ten per cent. The machine had ample power to travel around five miles per hour as long as it remained on top of the snow. When it broke through, the drum dug the snow away from itself and it was necessary to lift the sled to one side and get a fresh start.

The snow-surface was crusted to the extent that a man could walk on it without danger of breaking through. Where a twelve per cent side-hill condition was encountered, the sled had a decided tendency to slip sideways. When the slope was in the direction of rotation of the drum, it was necessary to dismount and straighten it out before proceeding, but when the slope was the other way the machine usually pulled itself back. On the down-hill run a speed greater than 15 miles per hour was attained, but at great risk of turning over because of skidding.







Figs.1,2,3--Air-cooled and spiral-driven Tucker snow motor-sled [Sled is powered by air-cooled Waukesha motor, especially designed for cold-weather operation. Frame is constructed of airplane steel tubing. Three sturdy runners carry most of the weight. The large front runner, equipped with fin-keel, serves (1) to give the spiral better traction--which results in more power and speed--and (2) to steer sled. The control is much like steering of an automobile and operates easily. Sled turns completely around in a little more than its own length--particularly important when driving through heavily wooded or rocky cross-country. Sled is geared to snow by revolving spiral drum which adapts itself automatically to any contour by use of cantilever-springs.]

This machine carrying two persons climbed a grade of between 30 per cent and 40 per cent without great effort, but with more weight the drum dug through the crust and stalled. On another occasion in soft snow great difficulty was encountered because the drum would continually dig in and plow out the snow surrounding it. It is my belief that if the major portion of the weight was carried by the out-board skis instead of on the drum, the performance in soft snow would be improved. On the whole, the machine is well built and thoughtfully designed.

However, when considering motor-transportation for snow-surveying parties, several points should be considered. The machine should enable one party to cover a sufficiently greater number of courses than a party on skis, or the same number in less time, to pay for itself during its useful life, or to reach areas not otherwise possible. It should be capable of progressing over practically all snow-conditions that may be encountered and in any weather. I do not believe that enough of these conditions are met by any of the present-day equipment to warrant acceptance without further investigation. However, the snow-mobile under test is strongly built to resist structural damage under extraordinary circumstances, is simple enough to be easily repaired in the field, and is light enough to be released when stalled or bogged.

One design that occurs to me, which I am not aware has been used, is that resembling a river-steamer driven by vertically floating stern- or side-wheels, or possibly the same device used by Tucker but placing a drum on either side revolving in opposite directions with opposite-hand helices to neutralize the side-thrust.

Regarding the driving device used by Tucker, if the weight of his sled were carried on the skis entirely it would be possible to decrease the diameter of the cylinder and increase the depth of the thread, thus obtaining a greater thrust-area or to substitute for the drum a conventional screw-conveyor making full use of the total diameter of the thread for traction.

The opinions expressed in this paper are personal only and were formed from observation without the advantage of experience and should be regarded accordingly. They are offered for consideration and discussion.

University of Nevada,
Reno, Nevada

DISCUSSION

E. M. TUCKER (Inventor, Tucker Snow Motor-Sled, Los Angeles, California; communicated)--Mainly, I want to inform you of the new motor connection made with the Franklin Motor Company in the east, which plans to have for the new sled an 80-horsepower air-cooled motor which will weigh not more than the present small Waukesha 14-horsepower motor which I demonstrated to you last winter.

This new motor with new spiral set-up, which I have now, will make 20 miles an hour through the same snow where we were stalled several times before. This adjustment will have double the traction and five times the power, with no more weight or less than 500 pounds.

I appreciate very much your suggestion of using levers to adjust the lateral ski to side-slopes and thereby to increase stability, but I am afraid that it would complicate the operation of the sled considerably and would increase weight and cost. It is hoped that other improvements will compensate.

IMPROVEMENT OF SNOW-SURVEY EQUIPMENT

Philip S. Cowgill

(Presented by Carl Elges)

This paper was also presented at the Stanford meeting [Trans. Amer. Geophys. Union, 1940, pp. 108-109]. The new design, suggested for a snow-sampler carrying-case will be completed for the Sacramento Conference proposed for next winter.

The accompanying design of "Cesco" face-shields (Fig. 1) suggests possible snow-equipment, particularly for those whose eye-glasses resist the use of the ordinary sun-goggle. Either green

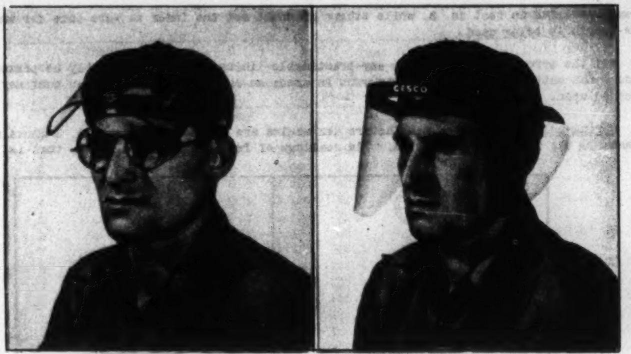


Fig. 1--Face-shields

or amber front can be obtained. These can be purchased from the Safety Equipment Department of the Pacific Metals Company, Ltd. (3100 Nineteenth Street, San Francisco, California). Similar face-shields are becoming a standard part of skier's equipment.

Sierra Pacific Power Company,
Reno, Nevada

TESTS OF MOUNT ROSE SNOW-SCALE NO. 101

J. C. Stevens

Mount Rose snow-scale serial No. 101 (Fig. 1) is a stock scale with improved index-adjustment and also a length-adjustment for each spring [see Trans. Amer. Geophys. Union, 1939, p. 76]. Three tests were made, each in a slightly different manner. In Test No. 1 the loads were applied successively without unloading. In Test No. 2 the load was removed after each reading; no adjustment of the index was made after its initial setting. In Test No. 3 the load was removed after each reading and the index was adjusted to zero after removing the load. These are more particularly described as follows:

Test No. 1 was made June 6, 1940, by Messrs. Rinker and Skoglund. The instrument was as assembled in the shop. An initial load of three pounds was applied (47.1 inches) and the index was brought to zero. Successive loadings by one-pound increments were then made without unloading the springs until the test was completed. Scale-readings were recorded independently by each observer. None differed by more than 0.1 inch.

Test No. 2 was made June 13, 1940, by Stevens and Rinker. It was the same as Test No. 1 except that an initial load of 2.31 pounds (36.4 inches) was applied and the index was brought to zero. Loads were added in one- and two-pound increments. The scale was read and checked by each observer; then the load was removed. No index-adjustment was made after its zero-setting for the initial weight.

Test No. 3 was made June 14, 1940, by Stevens and Rinker. This test was made similar to Test No. 2 after the springs had been adjusted slightly. The load was removed after each scale-reading and the index was also adjusted to zero before the next load was applied. This test probably simulates best actual field-use.

The results of these tests are given in Table 1 which shows the errors in inches and also in per cent of the theoretical values. The errors in per cent for each test are plotted in Figure 2. All three curves display the characteristics of this particular pair of springs. Another pair might have strong and weak zones at different scale-readings.

In field-use the load is removed after each reading. Test No. 1 therefore is not representative o field-practice. Some field-men doubtless reset the index before taking the sample as was simulated in Test No. 3, while others no doubt set the index to zero once for whatever tube-length is being used.

All the errors are well within any practicable limits that may reasonably be prescribed. It does not matter much how the instrument is used; an accuracy within one per cent may be depended upon.

Spring-adjustment--After manufacture the scales are tested as in Test No. 3 above and, if necessary, the springs are adjusted. The readings of Test No. 2 were all low, that is, the

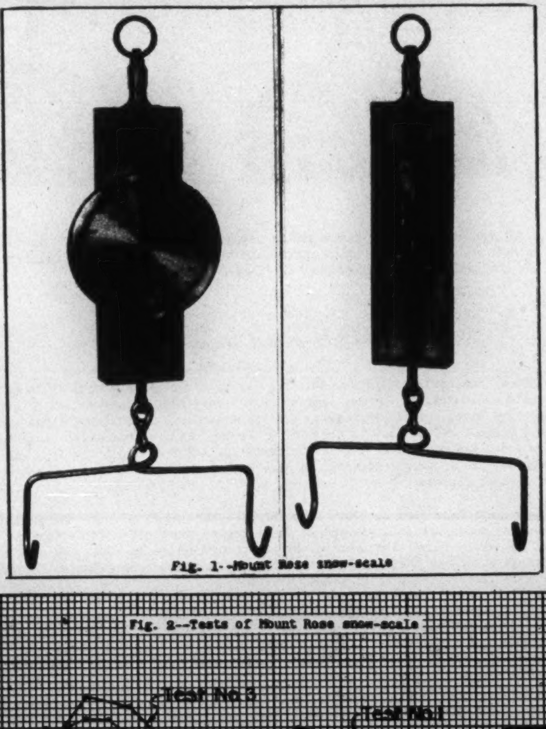


Fig. 1--Mount Rose snow-scale

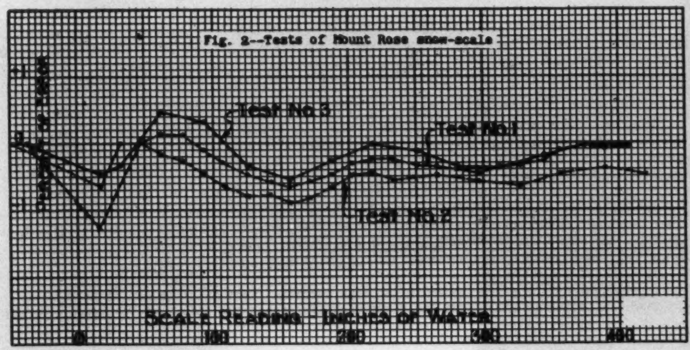


Fig. 2--Tests of Mount Rose snow-scale

Table 1

Pounds added	Theoretical precipit.	Test No. 1			Test No. 2			Test No. 3		
		Scale-reading	Error		Scale-reading	Error		Scale-reading	Error	
	inches		inch	o/o		inch	o/o		inch	o/o
0	0									
1	15.6715	15.6	-0.1	-0.64	15.5	-0.2	-1.27	15.6	-0.07	-0.46
2	31.3	31.3	0.0	0.00	31.2	-0.1	-1.32	31.2	-0.1	-0.32
3	47.0	47.0	0.0	0.00	47.0	0.0	0.00	.....	....	.....
4	62.7	62.8	+0.1	+0.15	62.6	-0.1	-0.16	63.0	+0.3	+0.47
5	78.4	78.5	+0.1	+0.13	78.2	-0.2	-0.26	.....	....	.....
6	94.0	93.9	-0.1	-0.10	93.6	-0.4	-0.43	94.3	+0.3	+0.32
7	109.7	109.4	-0.3	-0.28	109.0	-0.7	-0.65	.....	....	.....
8	125.4	124.8	-0.6	-0.47	124.4	-1.0	-0.80	125.0	-0.4	-0.32
9	141.0	140.2	-0.8	-0.57	139.9	-1.1	-0.78	.....	....	.....
10	156.7	155.7	-1.0	-0.64	155.3	-1.4	-0.90	155.9	-0.8	-0.51
11	172.4	171.4	-1.0	-0.58	171.0	-1.4	-0.81	.....	....	.....
12	188.1	187.2	-0.9	-0.48	186.9	-1.2	-0.64	187.6	-0.5	-0.27
13	203.7	203.1	-0.6	-0.30	202.7	-1.1	-0.49	.....	....	.....
14	219.4	218.9	-0.5	-0.23	218.4	-1.0	-0.46	219.3	-0.1	-0.03
15	235.1	234.6	-0.5	-0.21	233.8	-1.3	-0.55	.....	....	.....
16	250.7	249.9	-0.8	-0.32	.....	....	.....	250.4	-0.3	-0.12
17	266.4	265.5	-0.9	-0.34	265.1	-1.3	-0.49	.....	....	.....
18	282.1	281.0	-1.1	-0.39	.....	....	.....	281.1	-1.0	-0.36
19	297.8	296.5	-1.3	-0.44	296.0	-1.7	-0.57	.....	....	.....
20	313.4	312.2	-1.2	-0.38	.....	....	.....	312.2	-1.2	-0.38
21	329.1	328.0	-1.1	-0.33	326.9	-2.2	-0.67	.....	....	.....
22	344.8	344.0	-0.8	-0.23	.....	....	.....	344.1	-0.7	-0.20
23	360.4	360.0	-0.4	-0.11	358.8	-1.6	-0.44	.....	....	.....
24	376.1	375.9	-0.2	-0.05	.....	....	.....	376.0	-0.1	-0.03
25	391.8	391.5	-0.3	-0.08	390.3	-1.5	-0.38	.....	....	.....
26	407.4	407.9	-0.3	-0.07	.....	....	.....	407.2	-0.2	-0.05
27	423.1	.....	....	.....	421.1	-2.1	-0.49	.....	....	.....

springs were too stiff. A one-quarter relaxing turn of the adjustment gave the results of Test No. 3, substantially parallel but with less error.

Fatigue--The springs used were not designed for the heavy loads applied, for seldom does a snow-sample run over 150 inches of water, which corresponds to one revolution of the index-hand. These tests however were run up to over 400 inches of precipitation. For the higher loadings there was some evidence of fatigue. The index would continue to creep forward for five minutes or so and, when the load was removed, the index did not come back to zero at once. The following is illustrative:

(a) In Test No. 1 after the load was removed the index read 1.4; 15 minutes later it had dropped to 0.8 inch.

(b) In Test No. 2 with 15 pounds (235.1 inches) the time-intervals and scale-readings showing creep of the index were as follows:

Time	Scale-reading	Time	Scale-reading
0 minute	233.8	5 minutes	234.4
0.5 minute	234.0	11 minutes	234.5
2 minutes	234.2	16 minutes	234.6

(c) In Test No. 2 with 27 pounds (423.1 inches) the time-intervals and scale-readings showing creep of the index were as follows:

0 minute	421.0	10 minutes	422.4
3 minutes	421.5	15 minutes	422.6
6 minutes	422.0		

(d) After removing the 27-pound weight in Test No. 2 the time-intervals and scale-readings showing creep of the index were as follows:

0 minute	2.2	5 minutes	1.4
0.5 minute	1.8	11 minutes	1.2
1.5 minutes	1.7	85 minutes	0.8
3.5 minutes	1.5		

One would have to wait several hours for the evidence of fatigue to disappear entirely. By adjusting the index to zero between each loading and by taking the reading immediately the load is applied, the effect of fatigue is virtually eliminated.

Spalding Building,
Portland, Oregon

NEW SPRING-BALANCES BY JOHN CHATILLON AND SONS

John Chatillon and Sons of New York City in 1939 perfected for exhibition at the sessions of the International Commission of Snow at Washington, D. C., a spring-balance possessing a precision estimated at 99.98 per cent and capable of weighing a snow-sampler with snow-core one and one-half inches in diameter and 40 feet long. Because of this accuracy it becomes a fair substitute for a springless scale, which is too cumbersome for field-use. This balance can be used ~~also for weighing~~ snow-evaporation pans eight inches deep and 15 inches in diameter, or even somewhat wider. With this instrument the extreme conditions of the Pacific northwest can probably be met. [This balance was shown earlier at the Los Angeles and Spokane meetings and is discussed by Carl Elges and illustrated in Trans. Amer. Geophys. Union, 1939, pp. 75-77.]

Three other spring-balances have since been designed by the Company in a generous endeavor to produce an instrument that will best meet the needs of snow-surveyors. These are shown in Figure 1 and are numbered 1, 2, and 3 in order to facilitate reference in the accompanying discussion by correspondence that sets forth the purposes of each. Only essential excerpts are given below with suitable indications of source, namely, John Chatillon and Sons represented by

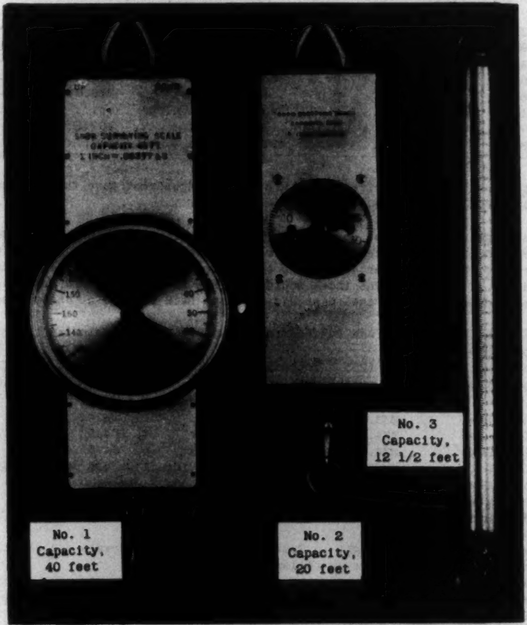


Fig. 1--New spring-balances by John Chatillon and Sons

George E. Chatillon, President, and B. T. Bortell, Vice-President, and J. E. Church and Carl Elges, Meteorologist and Assistant Meteorologist, respectively, of the Nevada Agricultural Experiment Station, at which the Mount Rose spring-balance was invented.

JOHN CHATILLON AND SONS--A further study has been made of your requirements for a scale to weigh snow and we contemplate conducting some further experimental work with a view to accomplishing, if possible, the production of a scale which would be more desirable to you from a standpoint of size and weight than the scale that was made.

Of course, we cannot inform you at this time whether we will be successful, as there are features connected with the work about which we are doubtful, but this matter is of interest to us and if we are successful in producing the scale, we will give you further particulars about it.

Meanwhile, we would like to have further particulars on the tubular balance, an illustration of which appears in the publication of the National Research Council, July issue, 1937, on page 608. There are not sufficient data for us to reproduce the scale and we were wondering if it would be possible for you to send us a sample of it for examination.

CARL ELGES--Dr. Church has asked me to ship you the three types of snow-survey scales that were in our hands here and I have done so.

Dr. Church also wanted me to send you a few remarks regarding the desirable points about the scales or those points that would be desired in a new scale. The scale by Leupold, Volpel and Company is the best one so far developed. It has the adjustment to zero for initial weight and it has sufficient capacity, but it is not as light in weight as the smaller tubular scale made by Julien P. Friez and Sons.

Relative to the capacity of the scale, it must be able to weigh a net weight of 150 water-inches in addition to the dead or initial weight of the sampler. The modern sampler weighs about four pounds per ten feet of length and our samplers are as long as 30 feet. The Friez scale, you will note, is limited to 12.5 feet of snow and for greater depths another scale is provided with an initial tension of about four pounds and supposedly a capacity of 20 feet of snow. This arrangement of having several scales is undesirable. Furthermore, the tubular scale is difficult to read and must be read twice since it is not adjustable to zero for the weight of the sampler.

J. E. CHURCH--In accordance with your letters at the end of the year my assistant, Carl Elges, sent you samples of three standard spring-balances, namely (1) by yourself, (2) by Leupold, Volpel and Company, and (3) by Friez and Sons for use in increasing the accuracy of the Leupold-Volpel and Friez scales by insertion of your improved spring or in designing an entirely new scale of your own for use in snow-surveying. All three balances have now been returned to us for our immediate needs.

We are greatly appreciative of your interest in improving the spring-balance and hope that you will have something to report to us, particularly for the meeting of the Interstate Snow-Survey Conference at Seattle, June 19-21, 1940. We shall be very happy to provide further details of our needs and restrictions as you may desire them. Your large scale will be put to practical test in the weighing of evaporation-pans of 15-inch diameter or larger. Extreme accuracy is needed for this work as well as portability to avoid carrying the evaporation-pans to a central point with the possibility of spilling the contents.

JOHN CHATILLON AND SONS--We are shipping you a sample snow-scale, which we hope will meet with your approval. We are enclosing herewith a calibration-chart (Fig. 2) showing errors of less than one inch.

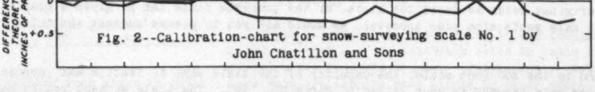


Fig. 2--Calibration-chart for snow-surveying scale No. 1 by John Chatillon and Sons

We have graduated the dial 200 inch by 1 inch for easier reading, making the total capacity 500 inches (see Fig. 1, scale No. 1). The scale has an adjustment of 12 pounds, which will make it possible to use all three-size samples, the longest of which we understand is 30 feet.

Referring to ours of April 29, 1940, we wish to advise you that we expect to have these scales ready on June 14, and would appreciate it very much if you would give us shipping instructions, so that they could be demonstrated at the meeting in Seattle, June 19-21, 1940.

The tubular scale (Fig. 1, scale No. 3) is made of brass, but if we are favored with the order, this scale can be made of aluminum. It has a capacity of 150 inches of water and is made with our iso-elastic springs. A zero-adjustment is provided at the top of the scale.

The dial-type scale (Fig. 1, scale No. 2) is on the style of our No. 260, but with the dial and pointer covered with cellulose acetate to prevent breakage in the field. This scale has a capacity of 250 inches of water with two and one-half revolutions of the pointer. A tare pointer-adjustment is also provided at the top of the scale.

We wish to acknowledge receipt of your telegram of June 13 in reply to our letter of June 11, and to advise you that the scales have been shipped today to you in care of the Hotel Edmond Meany, Seattle, Washington. We are pleased to advise you that these scales have been tested and although an accuracy-chart has not been made because of lack of time, they are as accurate as the previous scales submitted to you.

On the circular-dial scale (Fig. 1, scale No. 2), we feel that we have gone too far in trying to reduce the weight and believe that on the case the aluminum should be increased two gages.

J. E. CHURCH--The spring-balances were received at Seattle and were shown at the Meeting in connection with the discussion of snow-survey equipment. Your dial-balance was liked by the men even better than our Mount Rose model because of its proportions and the reduction of dial-numbers to 100 (Fig. 1, scale No. 2), rather than 150, which thereby makes the computation of the reading of the second or third turn of the pointer easier since only 100 or 200 must be prefixed to the dial-reading. Although the balance is three ounces lighter than the Mount Rose spring-balance, it is felt that no increase in weight should be made by increasing the gage of the aluminum unless you feel that the rigidity of the present gage is insufficient.

The polished metal of the case should be roughened in order to break up the mirror-like action of the present surface. On the snow-fields all glare should be avoided where possible.

The capacity of 300 inches which your scale possesses is 150 inches less than that of the Mount Rose scale. Neither scale, in the opinion of John C. Stevens, should be used to its full tension, since sufficient fatigue results to create inaccuracy unless a considerable time-limit is allowed between individual weighings. It is felt by some that the larger dial of the Mount Rose balance made the scale awkward to carry in the knapsack. However, most of us agreed that the dial could be read much easier in its present diameter than at the smaller diameter which your scale possesses. In connection with the publication of the picture of the spring-balances, your earlier chart of accuracy is being used. It is fully within reasonable limits of error. I understand that the Mount Rose dial is also closely accurate. Mr. Stevens has furnished a chart of the latest model [p. 906].

The tubular spring-balance (Fig. 1, scale No. 3) as made by you seems too long for comfortable use and the adjustment to zero is too limited for a heavy sampler. It seems to be almost impossible to create an adjustable type of spring-balance of the tubular form.

We all greatly appreciate your generosity in turning aside from your mass work to create new models. We shall be very happy to put both balances to further tests when next season's snow-surveys are made. Your large-size spring-balance will be put to use with evaporation-pans for which I believe it to be particularly adapted.

JOHN CHATILLON AND SONS--In regard to our suggestion that the gage of the aluminum be increased, this will only very slightly increase the weight of the scale and will hardly be noticeable, but will make a more substantial and rugged instrument.

We will be glad to accept your suggestion that the aluminum should not be polished, but left in its original color to avoid the glare, or the complete scale can be given a coat of paint, and if this meets with your approval, we would ask you to please suggest the color you prefer.

In regard to the 300-inch scale, the capacity of the scale sent to Seattle was purposely reduced, as per your request in your letter of March 25, 1940. The scale we sent you in March had a capacity of 500 inches and, therefore, the scale was made with a less capacity and more slender as requested.

It seems to us that the larger-capacity scale was not demonstrated at the meeting, and this scale should be compared with the Mount Rose balance both for size and capacity. In regard to Mr. Stevens' opinion, our scale can be used to full capacity at any time without inaccuracy, as the scale is so made that the springs cannot be overstressed and we have used springs of lower stress, so that the hysteresis and back-error is are practically eliminated.

In regard to the tubular scale, it can be made with an adjustment of about three pounds, but this, of course, would slightly increase the length. We wish to make the suggestion that if you would determine the smallest spacing between each inch or each mark that would be acceptable to you, and if this is less than on the scale sent you, a scale can be made proportionately smaller. The Friez tubular balance has a capacity of 135 inches while ours had 150 inches, and we have the spacing between the marks the same, namely, 0.080 inch.

We have now submitted a number of samples, but they have all been made without definite specifications; if you are now in a position to draw up desired specifications with the use of our iso-elastic springs which, as you will recall, are practically immune to temperature-variations, we will be pleased to furnish a quotation.

PROBLEM OF USING CALCIUM CHLORIDE IN PRECIPITATION-GAGES

Carl Elges

In the fall of 1939 the United States Weather Bureau installed a battery of three storage-precipitation-gages in Lamoille Canyon in eastern Nevada to be operated by the Forest Service. Since the gages were placed there upon request of the writer, considerable interest was taken in these gages. The gages in Lamoille Canyon are located at about 8,500 feet above sea-level and since the Forest Service personnel are withdrawn from the Canyon during the winter, a trip of about eleven miles must be made to visit the gages. Therefore it was planned to read the gages about once a month until the road was blocked by snow and then read them when the snow-surveys are made the beginning of each month starting March 1. During the past winter the road was open until approximately the first of the year and the last visit was made on December 30. From the date of installation in October until December 30 about 2.7 inches of precipitation had fallen and one carton of $CaCl_2$ had been added to each can. The gages had been charged as instructed in directions.

On March 1 when the gages were visited the observer recorded "Solution in gage partly frozen, snow level with tops of gages, probably some loss." Thereupon the writer decided to investigate the protection given by the various solutions of $CaCl_2$ so that the observer could be instructed relative to charging them in order that freezing would not occur.

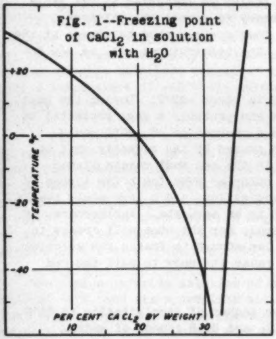


Fig. 1--Freezing point of $CaCl_2$ in solution with H_2O

Figure 1 was taken from The Chemical Engineer's Handbook by John H. Perry [1934 edition]. The percentages of $CaCl_2$ are calculated by means of the formula

$$P = 0.78[A/(A + W)]$$

where P is the percentage of $CaCl_2$ by weight, A is the amount of $CaCl_2$ (commercial, 77 per cent to 80 per cent pure) in pounds, and W is the amount of water in pounds.

One inch of precipitation in the eight-inch gage used will add approximately 29 ounces or 1.8 pounds of water to the solution. The percentages of $CaCl_2$ in solution created by adding increments of one inch of precipitation and adding one and one-half pounds of $CaCl_2$ after three inches of precipitation have fallen, as instructed by the directions furnished to observers, and the freezing points of such solutions as taken from Figure 1, are as in Table 1.

After obtaining the above data, it was thought desirable to test out the solutions cited in Table 1 to determine how reliable it was. Consequently, solutions representing each given in Table 1 were made and samples were placed in paper quart-cartons and set in the cooling room of the local ice-cream company. The temperature of the

Table 1

No.	Solution	$CaCl_2$	Water	$CaCl_2$ by weight	Freezing point
		lb	lb	°/o	°F
1	Original	1.5	2.0	33.4	....
2	After 1 inch precipitation	1.5	3.8	22.1	-6.0
3	After 2 inches precipitation	1.5	5.6	16.5	7.5
4	After 3 inches precipitation	1.5	7.4	13.1	13.5
5	Adding $CaCl_2$	3.0	7.4	22.5	-7.0
6	After 4 inches precipitation	3.0	9.2	19.2	2.0
7	After 5 inches precipitation	3.0	11.0	16.7	7.0
8	After 6 inches precipitation	3.0	12.8	14.8	11.0
9	After 7 inches precipitation	3.0	14.6	13.3	13.5
10	After 8 inches precipitation	3.0	16.4	12.1	15.0
11	After 9 inches precipitation	3.0	18.2	11.0	17.0

room was -20°F and cartons were left for three hours. When inspected at the end of three hours none of the solutions had frozen. The samples were left in the cooler overnight, the temperature during the night dropping to -30°F. When inspected the following morning all the solutions, excepting the original charge of the gage, were frozen.

Being rather puzzled that no freezing occurred when the solutions were left at -20°F for three hours, we transferred the solutions to open cans, for it was believed that the transfer of heat was impeded in the cartons. The cans were placed in the cooler at -20°F and after about three hours it was noted that most of the solutions were frozen to some extent. Further details of the observations follow.

__Temperature-record in °F__

8:55 am (time when solutions were put in cooler), -21.5
9:00 am, -21.5 11:00 am, -20.0 2:30 pm, -15.0
9:30 am, -20.0 12:00 am, -22.0 3:00 pm, -20.0
10:00 am, -19.0 1:00 pm, -20.0 4:00 pm, -20.0
10:30 am, -19.0 2:00 pm, -17.0
5:00 pm (time when solutions were removed), -22.0

__Inspections__

8:55 am, solutions put in cooler
11:00 am, samples No. 1, 2, and 5 showed no indications of freezing; all remaining samples had ice-crusts covering the top
4:00 pm, No. 1 solution was the only one that was not frozen
No. 2 and 5 were frozen but not throughout the solution and the ice formed was a slush; it could be stirred with a pencil but was firm enough that snow falling upon it would be supported
5:00 pm, condition of solutions was very much the same as at 4 o'clock
Solutions 2 and 5 were frozen throughout but not solid

From these experiments it appears that the solutions will freeze as indicated on the graph of Figure 1. It also seems that a long period of time is necessary to freeze the solutions, particularly when the solutions are near the strength at which they are supposed to freeze at the temperature to which they are exposed. In practice, of course, the temperatures will be low for long periods of time.

It is the writer's opinion that a gage should be protected to about -20°F. During the past three winters we have experienced mild weather here in the west and probably a gage protected to about -10°F would have met most conditions unfrozen. To insure a protection of -20°F would require a large initial charge of the gage so that the dilution caused by the capacity that is expected would not fall below 26 per cent $CaCl_2$. The solution in the can must remain liquid because when the snow ceases to melt in the can, the volume it occupies even for a few inches of precipitation would soon fill the can, thus subjecting it to wind-action, and a loss would result. Once the can is filled with snow, the record cannot be expected to be accurate. Furthermore, it is believed that the gage cannot recover when overloaded with snow, for the snow will freeze to the sides of the can and bridge over. When the temperature is low enough to freeze the solution in the can, it cannot be expected to rise sufficiently high to cause the snow to melt and run down into the solution.

An eight-inch gage charged so as to protect an expected ten inches of precipitation to 20°F below zero will initially require 26.9 pounds of commercial $CaCl_2$ and 35.8 pounds of water.

The storage-precipitation-gage is excellent where an observer is on hand to look after it and to keep the solution strong enough to prevent freezing at the prevailing temperatures. It is also an excellent gage to record the precipitation at the high-level mountain-stations during the spring when either snow or rain may fall and when the temperatures are not too severe. Where it is necessary to leave the gage for a month or more in subzero weather, however, it appears that the present gage, charged as now directed, will fail.

Nevada Agricultural Experiment Station,
Reno, Nevada

CALCIUM-CHLORIDE SOLUTIONS IN THE OPERATION OF PRECIPITATION-GAGES

Ashton R. Codd

The use of a salt for lowering the freezing-point of water is by no means a novel procedure, nor is the use of a brine-solution in a rain-gage a particularly new thought. However, the method of handling the brine-solution in a rain-gage throughout the season has proven to be a problem worth considering. About 1909 J. Cecil Alter began using the storage idea for precipitation in connection with his shielded-gage experimental work. He used a sodium-chloride solution covered with a film of oil, and weighed the precipitation with a spring-balance. The differential in weights converted to inches of water gave the amount of precipitation. This basic method has proven very successful in measuring all forms of precipitation, particularly snow.

During the early part of the winter of 1937, when the Alter shielded gage was given a rugged test in the mountains of Utah and Yellowstone Park, it became apparent that a different salt would have to be used in order to produce an anti-freeze solution which would withstand lower temperatures and yet one which would be economical enough for general use. Calcium chloride proved to be the answer to this problem, and when put into solution it was found to possess a number of desirable features. Its wide use in commercial refrigerating plants has brought the price down to where it can be used in quantity.

The low freezing-point of the calcium-chloride brine is its most outstanding characteristic. When mixed with water to a maximum strength of 29.6 per cent by weight, the freezing-point drops to a -59°.8 F. Figure No. 1 shows graphically the freezing-points of solutions of calcium chloride together with a comparative curve of sodium chloride. Another advantageous feature in the use of calcium chloride is the small amount of corrosive action on galvanized containers. The addition of sodium bicarbonate or sodium chromate will reduce the corrosive action to a point where the solution will show neither alkaline nor acid reaction when tested with phenol-phthalein.

Due to the lack of information regarding the calcium-chloride solution at lower temperatures than a -20°F, it was deemed advisable to subject several solutions to lower temperatures and observe the results. Five different strengths of calcium-chloride solutions and one sodium-chloride solution were mixed in glass beakers and placed in an insulated box with thermometers, circulating fan, ice-tray, and window for observation. Dry-ice was placed in a tray over the solutions, the box was closed, and the air was circulated through the ice past some dry calcium chloride (to reduce humidity) and around the solutions. The results showed that none of the calcium-chloride solutions congealed with a crust of ice, but formed a mushy, frazil ice. Even after a temperature of -65°F was maintained for two hours, the solutions were still of this consistency.

It was found that a ten per cent solution formed hydrates at -10°F and considerable frazil ice existed at -65°F. In a 26 per cent solution the salt crystals were formed at a -36°F and considerable feather-ice existed at -65°F. In a 33.4 per cent solution salt crystals formed in the bottom of the beaker at a temperature of -65°F. A 35 per cent solution did not start to form salt crystals until a temperature of -53°F was reached and no ice-crystals were noticeable at -65°F. A 40 per cent solution began to deposit large salt crystals at a temperature of -35°F, and at -41°F the beaker had about one-quarter inch of granular crystals in the bottom. A few feathers of ice were present at -65°F.

The sodium-chloride solution of 23 per cent began to form salt crystals at -5°F, became a solid at -8°F, and was a complete solid white mass at -65°F. A check-run was made of these solutions with virtually the same reaction. It was noted that as the solutions returned to room-temperature, the salt crystals went back into the solution without the necessity of agitating them.

Recent experience has indicated a stratification of density in solution due to fresh rain flowing under the oil-film and remaining on top of the denser solution. This would indicate a slow rate of fusion which has not so far been a serious condition, in that the ice which does form tends to do so below the oil-surface.

The utilization of a brine-solution in the precipitation-gages has been developed to a point where it has proven to be a feasible means of melting snow as it falls into the gage-container. No rain-collectors have burst due to freezing during the past two winter seasons. Current practice is to use an initial solution of 33.4 per cent principally because of the simplicity of mixing. The proportions are one and a half pounds of commercial calcium chloride (77 per cent to 80 per cent pure) and two pounds of water. This solution, being well above the eutectic point, gives considerable room for dilution and will stay in a liquid state at ordinary temperatures when first put into solution. The volume of solution is sufficient to permit economical operation and also to allow for dilution up to two and a quarter inches of added precipitation before theoretically freezing at a temperature of +10°F. At this point another one and one-half pounds

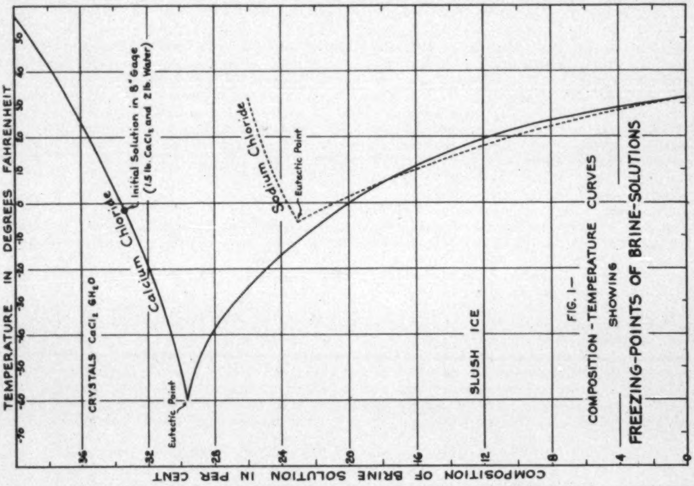


FIG. 1— COMPOSITION-TEMPERATURE CURVES SHOWING FREEZING-POINTS OF BRINE-SOLUTIONS

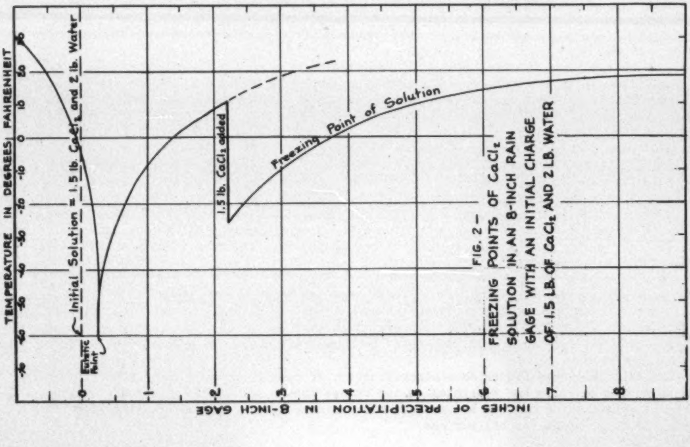


FIG. 2— FREEZING POINTS OF $CaCl_2$ SOLUTION IN AN 8-INCH RAIN GAGE WITH AN INITIAL CHARGE OF 1.5 LB. OF $CaCl_2$ AND 2 LB. WATER

of calcium chloride are added to the solution, thereby strengthening it and preventing freezing down to a theoretical temperature of -26°F. After another six inches of precipitation have been added, it is advisable to recharge the collector with a new charge of solution rather than to add the large quantity of salt necessary to bring the increased volume to a density that would be within safe temperature-range.

The economical operation of the gage played an important part in this matter. At a majority of the stations when nine inches of precipitation have fallen, it has been found that another new charge is sufficient to carry the gage into that period of the season when extremely low temperatures are not experienced. The gages then run on through the spring and summer months with a diluted solution remaining in the receiver until they are recharged in the fall and made ready for the winter season.

Figure 2 shows graphically a curve of dilution and freezing-points, starting with a standard volume of solution at 33.4 per cent and showing the path of freezing-points as increasing quantities of precipitation are stored in the collector. It should be remembered that this curve is theoretical, and that a slight amount of freezing will not turn the solution to a solid mass, but will form a mushy ice which is of little consequence.

The few reports received indicating that the contents of gages froze solid and the collectors filled with snow are believed to arise from the failure of the observers to follow outlined procedure. So far the greater number of the gages have been placed at locations where weekly or more frequent attendance has been available. In locating a gage where attendance is available only once or twice a season, the collector must be built of sufficient capacity so that a larger volume of solution can be used, thereby decreasing the rate of dilution.

The operation of an automatic recording precipitation-gage during the winter months at locations where temperatures below freezing are expected, presents another problem where a calcium-chloride solution covered with a film of oil has proven advantageous. The method of operation with the recording gages consisted of placing an initial charge of standard solution in the collector and floating a thin film of oil over the solution to prevent evaporation. The pen on the recorder is then adjusted to zero or to the one-inch line, and the instrument set in operation. The charts are changed by the observer as instructed, but the collector is not emptied until a recharge is found necessary or until the collector becomes dangerously full. The solution is strengthened at the three-inch mark and the collector is recharged at the nine-inch mark. During the past winter season 45 automatic recording precipitation-gages were operated successfully throughout Montana where temperatures of -43°F were experienced. Through Utah, Colorado, New Mexico, Arizona, Kansas, Oklahoma, and northern Texas approximately 100 recording gages were operated successfully with calcium-chloride solution.

It has been found advisable to coat the inside of the collectors with an acid-and-alkali proof paint to reduce the corrosive action of the brine-solution. This item is rather important and is strongly recommended for both recording and non-recording gage-collectors.

The economic value of using a calcium-chloride solution in a precipitation-gage to prevent damage to the collector from freezing temperatures and to melt falling snow, is not so much in the comparatively low cost of the calcium chloride as in the insurance of a year-round reliable precipitation-record at any station where freezing temperatures are expected. There is no break in the continuity of the record and no change in operation procedure from summer to winter, and the simplicity of routine is readily accepted by the observer.

U. S. Weather Bureau,
Salt Lake City, Utah

DISCUSSION

MERRILL BERNARD and **JOHN C. STEVENS** both agreed that monthly or shorter records would be preferable in studying precipitation to the longer accumulated seasonal records. However, a recording seasonal gage might be able to provide a continuous record of precipitation and evaporation in connection with the seasonal.

The Stevens seasonal snow-rain recorder [Trans. Amer. Geophys. Union, 1934, pp. 632-633, and 1938, pp. 718-720] has made provision for chemicals in its reservoir to convert snow into water and has adopted the tower and Weather Bureau wind-shield to gain greater accuracy of catch where the snow is deep and wind-swept. It has a capacity of a month or season as desired.

SNOW-SAMPLING EQUIPMENT FOR GRANULAR AND CRUSTED SNOW IN NEW ENGLAND

Paul Webster Bean and Frederick A. Bendtsen

(Presented by J. E. Church)

Establishment of snow-measuring stations

Snow-readings have been taken in the Androscoggin Valley every year for 30 years, but stations were not definitely located, that is, the same locality was visited each time but the place where readings were taken might have been a few hundred yards apart in two different trips to the locality.

Three years ago, a system was inaugurated whereby permanent stations were established and definitely located. This results in a better comparison of conditions from time to time during the winter, as well as making an accurate comparison between winters.

After this procedure was decided upon, trips were made to establish these new snow-measuring stations. In determining the location of these stations, an attempt was made to locate them so that representative readings for the area would result. They were spaced about 15 miles between stations and so located that tributaries which were known to produce heavy runoffs in the spring would be well covered by the survey when made. The high land at the eastern and western edges of the watershed was also covered by stations established at these points. (The extreme northern edge of the watershed is inaccessible in the winter, particularly as this is very nearly primeval forest-growth and much virgin timber still stands in this section).

In selecting the place where the snow-measurements were to be made, a wooded area was selected in most cases, though a few measurements are taken in sheltered fields for the sake of comparative readings. For the stations in the woods, a small clearing was found where the snow would have an unobstructed fall from above. Also, by having stations in the woods, the effect of wind drifting the snow was reduced to a minimum.

After finding the clearing, the underbrush was cleared away by use of an axe and grub-hoe, the ground was leveled off by use of shovel, and any protruding rocks were removed. The size of the cleared area is about 15 to 20 feet square when completed. The stations are marked by several blazes on trees surrounding the cleared area and then trees are blazed to make a trail from the station to the nearest point on the highway, where a sign is painted on a tree or post conspicuous from the road, to designate the number and location of the prepared snow-measuring station.

It may be added that to date about 50 of these stations have been established and that late in each fall, before the snow comes, each station is visited and any branches, new growth, windfalls, or any other obstructions are removed, so that accurate measurements can be made during the winter months.

Notes were made giving a full description of the station thus established for a permanent record. These notes include the number of the station, the location, the type of terrain (whether wooded or not), type of trees (if any), approximate amount of Sun, direction of the exposure, and, if on a hillside, the direction of the slope.

Equipment used in measuring snow

In measuring snow from an automobile, there are certain problems that are greatly simplified when compared to other methods of transportation for this work, but, at the same time, other situations arise that must be met which are not encountered in the other methods.

Following is a list of the articles and implements that are taken when the snow-measuring trip is made: Snow-tube; scale; twister; 48-inch iron rod pointed on one end; snow-shoes; shovels and axe; "Come-along" jack and rope; microscope; thermometer; ice-chisel; search-light; and the record-book.

Snow-tube--The snow-tube used in our work is made of aluminum tubing 50 inches long and of three-inch inside diameter. At the bottom there is a cutter with an inside diameter of 2.65 inches riveted to the tube. This cutter forms a collar within the tube that keeps the snow from sliding from the tube after the sample is obtained. On the top of the tube is a collar riveted to the tube to allow attachment of the twister to facilitate the obtaining of a complete core of snow.

The length of tube is quite satisfactory for measuring snow in this locality, as the depth of the snow is seldom over the 50-inch length of tube. When such a case does occur, the core may sometimes be slightly compressed, but this does not injure the value of the reading, because the texture of the snow in the Androscoggin Valley is such that the core of the sample taken is much shorter than the actual depth of the snow.

Twister--This is constructed of wood and can be fitted over the top of the snow-tube where slots are engaged to avoid slipping when rotated by its handles to obtain a sample core.

Pointed iron rod--This rod is a 3/8-inch iron bar, pointed on one end with graduations in half inches up to four inches, starting at the point of the rod. This bar is used to determine the depth of ice at the bottom of the snow when ice cannot be lifted with the sample taken.

Snow-shoes--The snow-shoes used are 12 inches wide by 48 inches long and are used in traveling from the automobile to the snow-station. One extra pair is usually carried.

Shovels and axe, "Come-along" jack and rope--These implements are taken for the purpose of keeping the car on the road. The "Come-along" jack has a capacity pull of three tons and a distance pull of five feet before a new hitch is required. A 100-foot length of 5/8-inch manila rope is used with this, to enable a hitch on a tree, or pole, from which to pull the car back on the road. Grab-chains are also advisable, since many icy slopes are encountered and the chains are required in order to climb these hills.

Microscope--This is a small hand microscope similar to a reading glass, but with greater magnifying power. It has a flash-light attachment that brings out the detail in a better light. The microscope is used to study the texture and general characteristics of the snow-sample at various depths from the surface.

Thermometer--This is an ordinary house thermometer used to determine the temperature of the snow 12 inches below the surface. It is pushed into the snow to this depth and allowed to remain until just before returning to the car.

Ice-chisel--This is a one-inch round iron bar, chisel-shaped on one end, and used to determine the thickness of ice on the main river.

Search-light--There are two types of lights in use now. One is similar to a miner's lamp that straps on the head and allows free use of the hands. The other type has a large five-cell battery with a six-inch light reflector-attachment. These are used for measurements taken after dark.

Record-book--This is used to keep a permanent record of the measurements made.

Procedure of snow-measurements

At all stations where snow-measurements are taken, the procedure is as follows: Three or four samples of snow-cores are obtained, weighed, and the average water-content is recorded. This is assumed to give an accurate and fair sample of the water-content of the snow in that particular locality.

The cores of snow are then examined through the magnifying glass to determine the size and shape of the crystals of snow. The snow-crystals that are fairly saturated with water are the size and shape of large salt crystals and have a water-color. The soft snow on the top is then flaky crystals, varying in size and shape and of a dull luster. This variation in size, shape, and color of snow-crystals is a good indication of how saturated the snow is and how much water it will absorb before a runoff can be expected.

In some localities it is not an uncommon occurrence to find from a half inch to one and one-half inches of ice on the bottom of the snow-cover. This is measured by driving an iron rod, on which is painted a scale, down through the ice. The type of ice and thickness is determined. By type of ice is meant whether it is clear blue-ice or a frozen snow. The type and thickness of ice-cover is a factor in determining the rate of runoff from the snow-field and how long it may take to melt away.

Throughout the entire drainage-system there are varying types of forest-growth. This difference in natural cover of terrain results in a portion of the drainage-area having a hard crust of earth, and other portions of the area having a wet, soft cover. This difference in cover is recorded and from these data it is determined how much of the area will give a quick runoff and what portion will absorb some water before runoff is started. This is important, because in this part of the country there are oftentimes heavy rains and thaws in January.

In the course of snow-surveying, readings are taken of snow-temperatures. A thermometer is inserted to a depth of a foot in the snow and a record of the temperature is made. This temperature plays an important part in determining when the "spring break" will come. The snow will hold rainfall up to a certain temperature. When that point is reached, rainfall and warm weather will convert the snow-cover into running water. Study of the daily weather-report and observed snow-temperatures permits reasonable estimates of the extent of the spring break and the probable magnitude of the spring flood.

From all the data gathered during the winter, such as water-content of snow, size and shape of crystals, ground-cover, ice-cover, and temperature, it is possible to determine the runoff and intensity of the spring flood and the time required to fill the storage-reservoirs with such accuracy that an error of over five per cent is a rarity.

Experimental work

Snow-tubes--While making measurements at regular stations in the winter of 1938-39, a series of readings were taken to get a comparison between the tube used for regular measurements and the Mount Rose sampler. It was found that the Mount Rose sampler was unsatisfactory for the conditions encountered in this area. The usual run of readings shows that when the texture of the snow was fine, the readings, when compared, showed errors of about five per cent to ten per cent, being both positive and negative at varying stations. When the snow was of a coarse texture, the error was much greater (up to 44 per cent) and these errors were all on the negative side, that is, the Mount Rose sampler recorded less water-content of the snow than the sample taken by the regular sampler showed.

The reason for this is believed to be loss of snow from the tube through the slots in the side and also that when going through crust-layers a true sample was not obtained. The idea was brought out that it may be possible that there were irregular voids in the snow caused by action of Sun and wind, so that a fair sample was not obtained due to the smaller diameter of the Mount Rose sampler.

[The following details are provided in the regional report of Paul L. Bean in the Annual Report of the Research Committee on the Hydrology of Snow (Trans. Amer. Geophys. Union, 1940, pp. 376-377): Experiments were made last year with the Mount Rose sampler and the regular sampler used by this company to determine which would be the better for use in the work in this area. The results obtained were convincing. The Mount Rose sampler appears to be inadequate for use in this section. From data obtained by a comparison of readings taken with the two samplers an error of up to 44 per cent was noted when two adjoining samples were measured. The Mount Rose sampler showed the lower water-content of the two samples, the size of the error depending on the texture of the snow. The coarser the snow (approaching "corn-snow" so-called), the larger the discrepancy shown by the Mount Rose sampler. It is believed that the error is due to loss of snow through the slots for determining the length of core and possibly to the small diameter of the sampler itself.]

With this in mind, three tubes were constructed late in the winter to try to determine if this were true, and if the size of the core obtained had any bearing on the accuracy of the measurement. The tubes had diameters of six, nine, and twelve inches, and were made of galvanized iron. From the results obtained, this Office was convinced that the diameter of the snow-tube (2.65 inches) used was entirely satisfactory in this area.

It is now intended to continue this work during the winter of 1939-40 and it is hoped that a report of some value may be submitted at a later date.

From a combination of the two samplers used last winter (the Mount Rose and the regular sampler) it is believed that a better sampler has been devised for use in snow-measuring in the Androscoggin Valley. A cutter has been made similar to that of the Mount Rose sampler, but with an inside diameter of 2.65 inches, to fit the tube that has already been in use several years. This has proven very satisfactory for work that has been done in the winter of 1939-40.

Since the texture of the snow does not permit the use of slots in the measuring tube, a new implement for rotating the cutter had to be devised. Two slots were cut in the sides of the protective ring at the top of the tube and a turning device fashioned from wood, with attached steel catches to engage the slots. This is an efficient twisting implement that can be quickly attached or detached over the end of the tube and is effective in cutting through heavy crust-layers, or through ice that may be present at the bottom of the snow-cover.

Temperature of snow--For the winter of 1940-41 another experiment is to be made in determining the temperature of the snow at various depths. For the present, two readings are to be taken, one six inches from the ground-level, and the second 12 inches from the top of the snow-cover.

An apparatus has been made whereby the thermometers are attached to an arrow-shaped piece of planking two inches thick. The bottom thermometer is at a fixed position six inches from the point and the top thermometer can be moved to any desired position on the shaft. The thermometers are protected by the point of the "arrow" while being pushed into the snow. When the point strikes the ground, a lever on the opposite side of the shaft is pulled, causing the thermometers to rotate downward 90° and to project beyond the point of the "arrow" into the snow at the desired depth.

It is hoped that data of some value can be obtained from this experiment and the relation of snow-temperature to rate of runoff can be determined.

Union Water Power Company,
Lewiston, Maine

DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--The snow-sampler used by the Union Water Power Company and being improved by the authors was designed originally by E. S. Cullings of Watertown, New York, for use in surveying the snow-cover in the Black River Regulating District in the Adirondacks. Details of the construction of the instrument and its use have been published in an article by him on the Adirondack Snow-Survey [Trans. Amer. Geophys. Union, 1936, pp. 545-550].

The failure of the Mount Rose snow-sampler to show as large water-content as the sampler of greater diameter may be caused by the coarser texture of the frozen snow of New England. However, large crystals in the Yellowstone Basin did not appear to impair the accuracy of the instrument as compared with the eight-inch precipitation-can used as a sampler.

On the other hand, by sealing the slots of one Mount Rose sampler with tape and leaving the slots of another open, no difference was found in the water-content of snow as obtained by the two. Details are given in a report on weight versus melting method for determining density of snow by J. J. McNutt and W. B. Alcorn [Trans. Amer. Geophys. Union, 1937, pp. 655-657] and in the following letter by Mr. McNutt (Las Vegas, Nevada, April 5, 1940):

"While at Bechler River in Yellowstone Park, Mr. Marr did furnish me with two improved snow-samplers. One was used with slots open, the other was used with slots covered with tape. There was no difference in water-content of snow as obtained by the two samplers. It was therefore concluded that granulated snow-particles did not enter the tube through the slots.

"In comparing the results between the snow-sampler and the eight-inch can, the sampler was found to give a higher reading than the can. This was found to be especially true when the snow became deep and contained frozen layers whose crystals were large. From my observations I would narrow it down to two possibilities. One is the air-pressure developed in the eight-inch can, and the other is the size of the granules or crystals which must be cut. The rough edge of the can, with air-pressure built up inside, might tend to push the larger granules or crystals to the outside of the can."

The problem of measuring the water-content of the ice-stratum that frequently underlies the snow-cover is especially difficult, for its texture may vary from coarse granular snow or ice to clear-water ice, thus creating inaccuracy when depth-measurement of the ice is combined with weight-measurement of the snow. Bean and Bendtsen met this difficulty by laboriously cutting a disk from the ice of the same diameter and circular contour as the snow-core and placing it in the sampler for weighing with the core of snow.

Kenneth L. Roberts, when Director of the Flood Control Survey, United States Department of Agriculture, for the Merrimack Basin, New Hampshire, suggested that the cutter of the Mount Rose Sampler be adapted to cut strata of ice as well as snow. Such a cutter was developed for the study of glacier-snow and penetrated ice to the depth of two inches. Beyond that depth, however, the sampler became frozen in by the resolidifying of the ice above the bulb of the cutter. The ice in New England is sometimes three and one-half inches thick.

A spiral ice-auger with hollow center seen at the Lewiston office of the Union Water Power Company may possibly provide a clue to the problem..

ACTIVITIES

O. W. Monson, Chairman

PROBLEMS OF THE DIVISION OF IRRIGATION IN FORECASTING WATER-SUPPLIES

W. W. McLaughlin
(Presented by R. A. Work)

This paper is published in "Soil Conservation" [v. 5, No. 6, pp. 148-151 and 163, 1939] under the title "Factors affecting runoff-forecasts based on snow-surveys."

Soil Conservation Service,
Berkeley, California

SNOW-ACTIVITIES OF THE UNITED STATES PARK SERVICE

R. D. Waterhouse

Snow-activities in Mount Rainier National Park were particularly emphasized and illustrated by movie film. The problem in providing ski-lifts for snow-sports is their removal in summer to avoid disfigurement of the landscape.

The National Park Service is now joining with the United States Army Engineer Corps in inaugurating snow-surveys at Mount Rainier for the study of flood-occurrence and forecasting. [For the text of a paper on this same subject at the Stanford University Conference, see Trans. Amer. Geophys. Union, 1940, pp. 134-136.]

(Mr. Kittredge, Regional Director, who was prevented by severe illness from attending the Stanford Meeting and planned to share in the Seattle Meeting, has been moved to the Grand Canyon as Superintendent.--Editor)

National Park Service,
San Francisco, California

RESEARCH ON SNOW BY THE FOREST SERVICE

Chas. A. Connaughton

Research on snow by the United States Forest Service is not new. Almost since the establishment of the national forests information on this subject has been sought. This information has been in demand not because of an interest in snow, per se, but because the national forests are being managed to obtain their greatest service as watersheds, and any management practice or scheme must be evaluated in the light of its influence on the accumulation and rate of melting of the annual snowfall. In this relationship between land-management and snow lies the interest of the Forest Service in snow-research.

Research on snow, as well as on other problems, was originally conducted by the administrative branch of the Forest Service. As time progressed, however, and the problems encountered became more complex, a separate branch of research was established with 12 regional experiment stations located in continental United States. At each of these stations several phases of research in wild-land management are in progress at present, and at least one-half of them are conducting some research on snow. The past research on snow by the Forest Service and the work now under way is described in the following discussion.

Completed research on snow

The first significant effort of the Forest Service in research dealing with snow dates back to 1910 when the now famous Wagon Wheel Gap study was started in cooperation with the Weather Bureau [see 2 of "References" at end of paper]. This study, located on the headwaters of the Rio Grande in Colorado, was designed to test the influence of forest-denudation on stream-flow. Two adjacent forested watersheds were selected and a rather complete series of ecologic and hydrologic measurements were made on them for a period of 16 years. In 1919 one of the watersheds was denuded of its forest-cover, after which comparative measurements on the two areas were continued until 1926.

Included in the measurements taken on these two areas was the factor of snow. At 19 stations on the forested drainage the depth, density, and rate of disappearance of snow were observed and on the denuded watershed similar data were accumulated at 15 stations. From the results obtained definite information was secured on the rate at which snow-melting is accelerated by forest-denudation. This relationship when translated into its effects on runoff brought out that stream-flow from melting snow is increased in volume, attains greater peaks, and is advanced in season by destruction of the forest-cover.

Almost at the same time the Wagon Wheel Gap study began to measure the influence of forest-cover on runoff, a somewhat similar study was started by the Forest Service in Utah [6]. This study involved two adjacent watersheds on which the influence of grazing and the density of herbaceous cover on runoff and erosion was measured. These watersheds are located at an elevation of approximately 10,000 feet on the Wasatch Plateau and an understanding of the hydrologic factors on them involved careful measurements of snow and translation of them into runoff-relationships. From this study it was determined, among other things, that the usable runoff is produced largely from snow-melt but that accelerated erosion is induced principally by rain rather than runoff from melting snow. Furthermore, this study has proven conclusively that herbaceous plant-cover is correlated closely with the degree of accelerated erosion. A similar relation with runoff from melting snow, however, is not so readily apparent. Rates of runoff during the spring melting-period is correlated more closely with air-temperature than any other factor. At the close of the first phase of this study, treatments on the watersheds were reversed as a check and this phase of the study is in progress at the present time.

Less pretentious but other significant studies on snow have been made and reported on by the Forest Service in several parts of the country. Griffin [5] in Oregon studied somewhat empirically the influence of forests upon melting of snow. He found that there was less snow in the forest than in the open at the beginning of the melting season, but that the snow remained 17 days longer on the average in the forest. Jaenicke and Foerster [7] studied accumulation of snow in a ponderosa-pine forest in Arizona. Their conclusions were somewhat similar to those reached in Oregon although the open-grown forests of the southwest had less influence on snow-cover than the denser stands of the northwest.

In Idaho, the author [3,4] studied rather intensively the accumulation and rate of melting of snow under different conditions encountered in a ponderosa-pine forest. The most significant conclusions were that as much as 25 per cent of the annual fall of snow could be intercepted and dissipated by mature tree-crowns and that the rate of snow-melt could be retarded by as much as ten days by a forest-cover. Based on this study the recommendation was made that the ideal forest for accumulating snow and regulating its melt should be interspersed with openings large enough to permit free fall of snow and yet small enough to be completely shaded from the sides. Meagher [8] studied the accumulation and rate of melting of snow in old growth and cut-over timber-stands as compared to the open. He found that melting was retarded by the cut-over forest about one week whereas the old growth retarded melting about two weeks. The deeper the snow, the more pronounced the influence of the forest-cover on melting became.

The much-discussed question of evaporation from a snow-surface was studied in Utah by Baker [1] of the Forest Service in 1915 and 1916. The technique used was adapted only to the winter season before melting began, but from the results obtained an estimate was made that approximately 14 per cent of annual snowfall on the Wasatch Plateau is evaporated directly to the atmosphere. Evaporation varied closely with air-temperature and had some relation to wind-velocity. Based on his, and other, observations, Baker concluded that once snow is deposited on the ground a forest-cover will aid materially in reducing evaporation.

Research on snow in progress

The studies mentioned briefly above are those which the Forest Service has completed and reported upon. Compared, however, to work under way at present, these earlier studies are relatively minor in both number and size.

Very recently a study of three major watersheds of about 500 acres each has been started in California. These watersheds are on the headwaters of Kings River in the high Sierra Nevada and support a dense stand of pine and fir. During the winter of 1939 and 1940 water-yields from these areas were measured; semimonthly snow-surveys on two courses and monthly surveys on 14 courses were made; and records were kept of ground- and snow-temperatures and rainfall and snowfall in both shielded and unshielded gages. After the hydrology of these watersheds is thoroughly understood the forest-cover will be modified according to best-known practices and the effects of this treatment on stream-flow will be determined. During the course of this study considerable intensive research will be done on the measurement of snow as a climatic factor and the correlation of this factor with runoff.

In Utah new studies have been started on Wasatch Plateau with the purpose of determining the effect of up-stream engineering measures on yield of water from melting snow. The question has arisen repeatedly whether or not watershed-improvement measures installed for the purpose of flood- and erosion-control materially modify the regimen of tributary streams. In order to secure information on this problem, detailed study of snow-conditions on selected areas was started in 1940. This study involves measurement of snow and its water-content, and mapping the rate of appearance of bare ground on areas which have and have not been treated with up-stream engineering measures. Also the surface-runoff or overland flow from snow-fields is being measured in an effort to determine whether water-yield from melting snow is derived principally from surface- or subsurface-flow. Indications, thus far, are that surface-flow is a factor only during very brief periods of higher than normal air-temperatures. If this is the case, watershed-improvement measures do not materially influence water-yield from melting snow and flood- and erosion-control measures designed primarily to handle summer cloudbursts do not affect adversely the usable discharge from a drainage-basin.

In the southwest the Forest Service is concentrating snow-studies to determine how the annual accumulation of snow is dissipated. This problem is being attacked on large and small watersheds and on lysimeters where measurements of the snow and its water-content and the rate of snow-melt are made in conjunction with measurements of surface-runoff and seepage-flow. From these studies, data will be secured on how much of the snow is lost by evaporation, how much of it melts and runs off as surface-flow, and how much of it enters the soil to replenish soil-moisture or produce ground-water runoff. This study is being made under conditions typical of certain watersheds in the southwest where the snow-cover is intermittent throughout the winter season.

In Colorado an intensive program of research on snow has been in process of development since 1938. These studies are being concentrated on the headwaters of the Colorado River at an elevation of approximately 9,000 feet. Research in this locality began originally with the establishment of 20 five-acre plots designed to make a combined study of the influence of different methods of cutting of a lodgepole-pine forest on the accumulation and rate of melting of snow and the growth of timber following these same methods of cutting. On each of 20 plots a series of 25 snow-measurement points was mechanically located and permanently marked. Each point of measurement was described as to crown-cover, exposure, per cent of slope, and position on slope relative to major ridges. This resulted in 500 carefully described points of snow-measurement on 100 acres, thereby insuring a good representation of all crown-conditions occurring within the stand.

At each of these permanently marked points, weekly measurements of snow-depths and water-content were taken during the springs of 1938 and 1939. Measurements began before the snow-mantle lost any water and were made for the purpose of determining the amount of water accumulated in snow prior to and during the period of spring melt. From these measurements the average water-content of the snow was computed weekly for each plot during the melting-period and for each season for all plots. These data were then used in a correlation-analysis to express the influence of crown-canopy density and other physical factors on storage and rate of melt.

Results of two years' observations [9] of snow-conditions in this uncut stand of lodgepole pine may be summarized as follows: (1) Forest-canopy density is an important factor affecting snow-storage and melting within the virgin forest, snow-storage was greatest in the largest existing openings which were about 60 feet in diameter; (2) per cent of slope and position of point of measurement on the slope appeared to have no measurable relation to the volume of stored snow in the forest; and (3) apperently the canopy of a virgin lodgepole-pine forest is too dense for optimum storage of snow, indicating that properly managed cutting will increase the effectiveness of the forest as a watershed cover.

After the two years' observations of these plots under virgin conditions, they were cut-over by four different methods during the winter of 1939 and 1940. These methods of cutting range from practically a clear cut to a light selection-cut. In addition, one series of plots was left uncut as a check. In the future snow-storage and melting on these plots will be studied as in past years and comparisons will be made of conditions on the same plots before and after cutting and of conditions on different plots which were subjected to varying degrees of cutting. At the same time snow-studies are being made, the growth of timber on these various plots will be determined and by combining the results the most suitable method of cutting from both the forest and water-yield standpoints can be recommended.

Because of physical and financial limitations, plots for study of methods of cutting were not located so that stream-flow could be studied coincidentally. To answer this need a nearby watershed approximately 700 acres in size with a timber-cover similar to that on the plots was controlled for year-long measurement of precipitation and water-yield. While the effects of the various methods of cutting on the plots are being studied, the hydrology of this watershed will be determined and, by the time an optimum method of cutting is indicated from the plot-studies, the natural characteristics of the watershed will be understood. The most desirable method of cutting as indicated by the plot-studies can then be applied on a watershed-basis and its effects on hydrology of the basin can be accurately determined by comparing data secured before and after cutting.

Supplementing the method of cutting and watershed-studies, a group of short-time studies has been carried on to provide additional and supplemental information on the optimum size of forest-openings for snow-storage and melt. During the spring of 1940, a series of 30 openings in young stands of lodgepole-pine were selected for intensive study. These openings varied in diameter from four to 47 feet and the tree-heights surrounding them averaged about 15 feet in one stand and about 25 feet in another. In both stands snow-storage was found to be correlated strongly with size of opening. Maximum snow-storage in the stand of smaller trees was in openings ten to 25 feet in diameter, with less snow in both larger and smaller canopy-openings. In the taller stand maximum storage was in somewhat larger openings, varying from 15 to 26 feet in diameter. These data confirm the plot-studies which have established that maximum accumulation of snow in forest is obtained in openings and have added the further information that the optimum size of these openings depends upon the height of the trees surrounding them.

In another short-time study, data have been secured on the relative effectiveness of young lodgepole pine, aspen, and sage-brush in storage and retention of snow. This study was in a single broad valley where the variations of slope, exposure, and other factors were minimized. Results indicate that annual snow-storage is somewhat greater on land with a sage-brush cover than on similar areas supporting aspen or lodgepole pine. As melting progresses, however, the differences between snow stored in the various plant-types decrease. Finally the conditions prevailing at the beginning of the melting season are entirely reversed with the most snow in the lodgepole-pine stand and the least in the aspen and sage-brush, with very little difference between the latter two.

Other studies in Colorado are in progress or planned for immediate installation on the more fundamental aspects of snow-research. Evaporation from snow, temperature within the snow and the soil immediately beneath, and moisture of the soil in relation to recharge from snow are the subjects of this more intensive research. Equipment for determining temperatures and soil-moisture is being set up at present for use during the winter of 1940-41, whereas evaporation from snow was studied rather intensively during the melting season of 1940.

The snow-evaporation study in progress is being approached by making an effort to determine moisture-losses from impervious surfaces or pans with areas of 1, 4, 20, 100, and 400 square feet. With the two smallest pans evaporation is measured by weight, while from the larger surfaces it is obtained indirectly by daily measurement of changes in water-content of the snow on the pans and of seepage-runoff from the snow-column. Analysis of one season's data shows a high correlation between the evaporation-rates from the two smaller pans. Results from the larger areas are inconclusive, however, owing largely to inaccuracies in the first intensive efforts in measuring the water-content of the snow stored on the impervious surfaces. It is anticipated that in another year at least some of the difficulties will be solved.

This study of evaporation involves certain innovations which are of special interest. Recognizing that satisfactory instrumentation for the study of evaporation from snow has not been developed, it was decided to attempt to measure accurately the precipitation on a rather large area of 400 square feet, to collect all runoff, and then to calculate evaporation as the difference between precipitation and runoff. In order to do this a circular galvanized iron, water-tight platform with drainage to a pit was constructed and covered with a thin layer of gravel and litter. A six-inch rim enclosed this platform. All construction was completed prior to the first fall of snow in the autumn. Just prior to the beginning of spring melting the water-content of the snow-cover was determined as accurately as possible and all runoff was measured during the melting season. Obviously this method has disadvantages, although it was hoped that the very size of the evaporation-surface would take care of certain troubles ordinarily encountered in working with snow-columns. Only the results of the future will determine whether or not this method of study will be successful.

In the eastern United States the Forest Service is conducting studies on snow in reference to flood-control. In Pennsylvania snow-depth, snow-water content, and frost-penetration into the soil were observed on 37 one-acre plots in eight different small watersheds during the winter of 1939-40. Data collected are not completely compiled but preliminary results indicate the effectiveness of the forest in reducing loss of water from the snow-cover during times when tributary streams are in flood-stage.

On the Smith River Watershed in New Hampshire a study has been started on the effectiveness of a forest-cover in reducing flood-peaks. Tentative results indicate that a forest-cover retards snow-melt enough to have a significant effect on floods. Further study is necessary, however, in order to draw definite conclusions applicable to the locality and conditions involved.

The future of snow-research

In the preceding discussion a brief description of research on snow by the Forest Service has been presented. The results of these studies are or will be of great importance in perfecting plans for watershed-management. In terms, however, of the magnitude of the problems involved and the many unanswered questions, research has barely scratched the surface.

In order to secure the greatest watershed-service from lands on which snow falls, a knowledge must be developed which will permit adoption of management-technique designed to insure optimum yields of usable water. How can existing forests be managed to enhance water-supplies? Should management-practices vary with topography so that good and bad effects of slope and exposure on snow-melting and accumulation will be either accentuated or reduced? How should new forests be planted in order to secure their great service as watershed-factors? Should they be continuous, arranged as wind-breaks,or planted in groups? What is the best plant-cover on watersheds where there are reservoirs completely controlling the stream-flow and rate of melting of snow is not a factor? How does a snow-cover influence frost-penetration into the soil and how does this enter into flood-control and the use of up-stream engineering measures? These and many, many other similar questions must be answered and in securing applicable results the Forest Service feels a strong responsibility.

As it so happens the Forest Service has been able to develop research-centers in many of the most important wild-land areas in the United States in recent years. These centers are in a position to conduct the research on snow which is needed and, as rapidly as funds and facilities permit, the necessary studies will be undertaken. Under prevailing arrangements, however, extreme difficulty is being encountered in merely carrying on work now in progress and only through considerable expanded effort can research on snow be given the emphasis it justly deserves.

References

[1] F. S. Baker, Some field experiments on evaporation from snow surfaces, Mon. Weath. Rev., v. 45, pp. 363-366, 1917.

[2] C. G. Bates and A. J. Henry, Forest and streamflow experiment at Wagon Wheel Gap, Colorado, Mon. Weath. Rev., Supp. No. 30, 1928.

[3] C. A. Connaughton, The effect of forest cover on snow melt, Forest Worker, March 1933.

[4] C. A. Connaughton, The influence of vegetation on the accumulation and rate of melting of snow, J. For., v. 33, pp. 564-569, 1935.

[5] A. A. Griffin, Influence of forests upon the melting of snow in the Cascade Range. Mon. Weath. Rev., v. 46, pp. 324-327, 1918.

[6] C. L. Forsling, A study of the influence of herbaceous plant cover on surface runoff and soil erosion in relation to grazing on the Wasatch Plateau in Utah, U. S. Dep. Agric. Tech. Bull. 220, 71 pp., 1931.

[7] A. J. Jaenicke and M. H. Foerster, The influence of a western yellow pine forest in accumulation and melting of snow, Mon. Weath. Rev., v. 43, pp. 115-126, 1915.

[8] George S. Meagher, Forest cover retards snow melting, J. For., v. 36, pp. 1209-1210, 1938.

[9] H. G. Wilm and M. H. Collet, The influence of a lodgepole-pine forest on storage and melting of snow, Trans. Amer. Geophys. Union, 1940, pp. 505-508.

Rocky Mountain Forest and Range Experiment Station,
Fort Collins, Colorado

DISCUSSION

J. CECIL ALTER (U. S. Weather Bureau, Salt Lake City, Utah)--I believe that Dr. Church reported many years ago, as the result of his studies of conservation, that forests with glades were ideal conservers of snow.

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--Yes, as early as 1912, but the Forest Service then felt that forests must be cut by sizeable sections and not trimmed into glades.

H. T. GISBORNE (Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana)--But now watersheds are being managed for purposes of developing water as well as timber, and the emphasis has changed especially on the National Forests. "Multiple use," to serve all public needs rather than single-purpose management such as silverculture alone or recreation alone, is the present practice.

(The ideal forest [Sci. Amer. Supp., September 7, 1912] from the viewpoint of conservation is the one that can conserve the maximum amount of snow until the close of the season of melting. Such a forest should not be dense enough to prevent the snow from reaching the ground and yet should be sufficiently dense to afford ample shelter from Sun and wind. The fir-forest possessing a maximum number of glades or a forest of mountain-hemlock meets these requirements both theoretically and practically. However, glades can be produced in any dense forest by the simple operation of cutting, the diameter of each glade being so proportioned to the height of the trees around it that the snow in early spring is effectually screened from the Sun. Such a forest, when viewed from above, would resemble a gigantic honeycomb, the glades of the forest being equivalent to the cells of the comb.--Editorial note.)

SKI-ETIQUETTE AND SKI-SAFETY

J. Carlisle Crouch
(Presented by R. C. Farrow)

[A series of radio talks given over radio stations KMED, Medford, KFJI, Klamath Falls, and KOAC, Corvallis, on January 5, 12, and 19, 1940, in connection with snowcasts. Mimeographed copy made available by The Oregon Cooperative Snow-Surveys, Medford, Oregon. Requested because of its timeliness for presentation at Seattle.]

Skiing and other forms of snow-sports are generally recognized today as one of the most wholesome, healthy, and exhilarating forms of outdoor recreation and one in which the general public can and does participate. Since Crater Lake National Park was first made accessible for visitors in the winter of 1935-36, we have seen snow-sports grow in popularity and we have seen those who participate in them derive immeasurable enjoyment, relaxation, and fun. At the same time, we have noted definite hazards and risks in the sport, many of which, we believe, can be eliminated and others reduced to a minimum. Since snow-sports are largely a group-endeavor, there are a few rules of the game both on and off the field, which, when observed by all, add to the general fun; but which, when ignored or only partly observed, detract from the common enjoyment.

The usages of skiers on the trails and snow-fields which go to make up what is generally referred to as "ski-etiquette" are few in number and simple in nature. They have been established through the experiences of skiers themselves and not just enunciated by some self-appointed arbiter of snow-sports. Each usage established and in practice is an exposition of common sense, consideration for the other fellow, and rules of safety.

"Ski-etiquette" is largely a subjective matter, whereas ski-hazards are largely objective. A hidden obstruction in a trail is a hazard, while stepping on another's skis represents, so to speak, a breach of "ski-etiquette."

Let us now consider some of the more important usages which go to make up "ski-etiquette."
Number 1--It hardly seems necessary to mention the importance of a skier taking his own equipment when leaving his car or otherwise going out to enjoy the sport. It happens on occasions when, in our eagerness to "get going," we might take skis, poles, or some other part of another's equipment. The results are obvious.
Number 2--Conversely with the established practices on the golf-course, where the faster golfer may catch up with and pass the slower one, in the case of snow-sports, the slower skier has the right of way. Refrain from yelling "trail," "track," and so forth to the slower skier.
Number 3--It is perfectly natural for skiers, even the experts at times, to fall or to "take a spill," as the saying goes. "Ski-etiquette" directs us in this event to fill the hole

or the "bathtub" before continuing on our way. This is particularly important on the trails or other places where others are following or will follow.

Number 4--It is important that a party of skiers travel in a group together. If for any reason a member of the party lags behind or takes a different course, keep in communication with him until he catches up.

Number 5--Try to avoid stepping on another's skis or running on to them with your own. Interference with others might have serious results.

Number 6--In using established trails, ski only on the marked routes and do not take steeper slopes adjacent to the trails as others will follow who may not be sufficiently experienced to negotiate them in safety.

Number 7--Respect the rules and regulations, buildings, and property of the area in which you participate in winter sports. The few and simple rules have been promulgated for your safety and are all conducive to a fuller enjoyment of the sport if observed. The overnight accommodations, warming huts, and other facilities are provided for your convenience. Remember that others will follow you in their use and you, yourself, will no doubt use them a number of times in the course of a winter season.

Skiers have the reputation of being one of the most independent and self-sufficient groups of outdoor recreationists--otherwise they would not take up the sport--and are known far and wide for their admirable sportsmanship. They are always ready and willing to offer assistance to those who run into difficulty or meet with an accident. Such a spirit and practice on the part of skiers account in no small measure for the abounding fun of the sport.

Some of the simple rules in effect in Crater Lake National Park prohibit skiing on the highways, the use of toboggans and sleds on the highways, towing toboggans, sleds, or skiers behind automobiles, parking on the highways other than in designated areas, and the standard rules of safe driving. The Service has provided a warming hut on the Rim of Crater Lake for your convenience and for your use in waxing skis, adjusting and repairing bindings, warmth, and for lunches. Use this building generously for these purposes so that it will not be necessary to use other buildings for the same things.

Up to this point we have discussed some of the usages developed through the experiences of skiers which add to the attractions of the sport. We should like now to discuss briefly some of the more important hazards of skiing, those factors which tend to detract from the fun of the sport.

The most important hazards of a subjective nature to skiing are poor physical condition, fatigue, and carelessness. Lack of confidence in one's ability--due in a large measure to an absence of instruction, training, and practice--also represents a hazard as statistics show that most injuries occur to the beginners and novices. Injuries to expert skiers do occur occasionally, sometimes as a result of hidden obstructions and at other times by taking risks which they know to be unsafe.

Most of us, including office and other indoor workers, devote one day a week to snow-sports, hence attempt to get as much skiing during that 24-hour period as possible. After indulging in this strenuous physical exercise most of the day, our muscles get tired, our reflexes and reactions lose some of their keen edge, and, although the desire to ski diminishes little, our physical self slows down. It is important that we give ourselves a margin of safety this side of the condition of fatigue.

One factor of skiing which is most conducive to safety is controlled skiing. This type of skiing can be attained only through qualified instruction, training, or practice. Once this type of skiing has been mastered the skier can control his speed and direction which lessens his chances for falls and other contributory causes of injuries.

Faulty bindings, faulty skis, or other items of faulty equipment constitute a serious hazard. Such equipment precludes controlled skiing or safe skiing.

Ski-poles rank as a serious hazard to your own safety as well as that of others when handled improperly or carelessly. Ski-pole tips, especially in conjunction with falls, have been prominent in winter-sports casualties. The steel points are obviously dangerous and produce the serious puncture wound as well as open cuts. The positions in which the poles should be carried whether walking or skiing are important from a safety standpoint. When walking, the poles should be carried nested together with the points out forward and not just thrown loosely over the shoulders. When skiing down hill, keep the holes trailing well back of the body and with the points down low. The poles should be handled carefully at all times to avoid spearing another skier.

Falls take a position in the forefront with respect to causes of snow-sports injuries. They may be induced by a lack of knowledge of and experience in skiing, fatigue, poor physical condition, carelessness, or hidden obstructions. Injuries resulting from falls include fractures, punctures, bruises, abrasions, sprains, and others. Ski-poles quite often contribute to injuries resulting from falls, either by the pole shattering and producing splinters and spikes to enter or to cut the body, or by the point causing a punctured wound or an open wound. Injuries incurred by falls might also result from contact with the points of the skis, although this type of injury is much less prevalent.

An analysis of the accident-reports of Crater Lake National Park reveals that a majority of the injuries occurred in late afternoon. At this time, the snow becomes much faster due to freezing, fatigue has entered the picture, and the skier finds control difficult or even impossible. The majority of the leg-fractures occurred on the left side and just above the ankle-joint. Ankle-sprains occurred more often on the left leg. Open wounds were most generally caused by the points of ski-poles.

The foregoing discussion stresses the importance of guarding against a fatigued condition, the added risk involved in late-afternoon skiing, when the snow begins to freeze, the extreme danger of poles when improperly or carelessly handled, and the all-importance of controlled skiing. We might be facetious and make the remark that we have seen an advantage in padding or otherwise strengthening the left leg or leaving it at home before going out to ski. In any event, begin your skiing by obtaining good quality, dependable equipment, learn how to control your skiing, observe the few and simple rules of snow-sports practices, and the sport will be most enjoyable to you and your associates.

The two preceding instalments in this series of discussions have attempted to indicate some of the usages evolved by skiers, hazards and dangers inherent in the sport, and ways and means by which they may be eliminated or reduced in number and extent. The purpose of this final instalment is to summarize the more important angles developed and to leave with you several additional thoughts relative to ski-safety.

In this rapid and brief review, we might mention again that the slower skier has the right of way; in the event of a fall, particularly on a trail, stop and fill up the hole; remain with your party; do not, when leaving your car or starting out to ski, get some other's equipment; do not step on another's skis or run across them; follow the marked trails; select safe slopes to make new tracks as others--some of whom may not be as qualified as yourself--will surely follow, and respect the rules and regulations, buildings, and property of the area in which you take part in snow-sports.

Fatigue, poor physical condition, lack of confidence, and carelessness represent the more serious subjective hazards in skiing. Hidden obstructions, faulty equipment, ski-poles and skis, and other skiers represent some of the more important objective hazards. Let us emphasize again the importance of mastering controlled skiing and many of the hazardous conditions discussed will be automatically eliminated.

We should now like to call to your attention the actual and potential dangers involved in small parties taking cross-country trips. Such parties should be fully equipped to meet emergencies and should consist of not less than four members, so that, in the event one member meets with an accident, two can return for aid while the third remains, or the three may transport the injured by improvised transportation-methods. Such parties should register out, giving the names, destination, route, time expected at destination, and time expected back.

It is not within the scope of this discussion to go into first-aid measures in connection with snow-sports injuries. Suffice it to state the importance of applying ample heat to the injured. We know that injuries which occur in the summer time reduce the heat of the body which contributes to the condition known as shock. Application of sufficient heat is even more important in the winter, for in addition to a reduction of body heat by virtue of the injury, the cold weather and cold snow further reduce it. We should also like to emphasize the care to be taken during reduced circulation in the application of splints and bandages which might make freezing possible.

Your attention is called to the emergency first-aid and safety-facilities available at Crater Lake National Park. Each member of the ranger-force is trained in first aid and has had experience in its application. There are three fully equipped first-aid stations in the Park located at the Rim Area, Park Headquarters, and Annie Spring. In addition to the park-rangers and park-equipment, the Crater Lake Ski Club has organized a ski-patrol, most of the members of which are qualified in first aid. There are usually one or more doctors present during the week-end period. We want to urge you to report your injuries, no matter how minor they might seem at the time, to the rangers, or through the Ski Club members to the rangers.

The importance of reporting and caring for the so-called minor injuries, especially sprains, should be stressed. We have already indicated that the skier is an independent individual and is reluctant to admit that he has met with injury, be it ever so minor in nature. If not cared for properly, a sprain might become a serious injury and ultimately result in involved complications.

There is yet another danger from snow-sports and that is sunburn and snow-blindness. In addition to the direct rays of the Sun in high altitudes there is the added danger from the light reflected from the snow. Special precautions should be taken to guard against sunburn and snow-blindness on bright days during the winter and also in the spring when there is a tendency to discard clothing in order to get a good sun-tan in advance of the summer season. In addition to the danger of sunburn in the spring when clothing is discarded, there is the added danger of exposure in the event of an accident. When weather-conditions warrant dispensing with surplus clothing, this should be carried with the skier for protection against exposure if he meets with an accident or if he meets another who has been injured.

Crater Lake National Park,
Crater Lake, Oregon

ICE-CRUSTS AND SNOW-SETTLING AT SNOQUALMIE PASS, SEASON OF 1939-40

Phil E. Church

The writer, new in the field of snow, chose to observe the building up of the snow-cover and its attendant changes, by dyes and identifying ice-crusts, at Snoqualmie Pass (altitude 3,019 feet) because of the short distance from Seattle (63 miles), accessibility (road is open all winter), and excellent supporting weather-records which are kept by Mr. Maybie of the State Highway Patrol. Eight trips were made between December 27, 1939, and April 4, 1940. The first of these was purely a reconnaissance trip in which the location of a convenient site, not disturbed by skiers, and yet level and treeless, was chosen. On January 18 the first profile was cut, and the succeeding six followed at approximately ten-day intervals until April 4. The only available equipment was a yardstick, a thermometer, and several bottles of various colors of dye. No measure of the water-content could be made owing to the lack of requisite equipment.

The amount of snow on the ground, the total fall, and the temperatures were far from normal during the whole snow-season. There was some snow on October 23 and 25, light snow on two days in early November, and then none until December 9. Thus there was no snow on the ground during the month-interval between November 8 and December 9, and as a result the whole of the November rain was lost to the snow-cover as well as some in December. During the period of November 1 to December 9 more than ten inches of rain fell. The normal melted precipitation (15-year average) for that period is slightly more than 15 inches, a fair portion of which is probably stored in the normal snow-cover of about 25 inches (15-year average for December 9).

After December 9 the snow-cover built up to 20 inches in depth in a few days, remained quite constant till near the end of the month, at which time the depth finally reached 28 inches. It was during this month that crusts K and N (see Fig. 1) were formed. December was wetter than normal (total 19.26 inches against 15.71 normal), but the snow-depth was far short of average (50 inches for December 31, 15-year average).

January was warm and dry. A combination of rain, sunny warm days, and a cold spell developed crust L (see Fig. 1). Snow-depth was less than usual, for by the middle of the month there were but 37 inches on the ground compared to the 15-year average of 66 inches. On January 18 a profile was cut and the exposure showed the bottom five inches to be old snow, well packed, and firnification well advanced. An imperfect crust (N) some three inches thick followed, then old snow whose top was 19 inches above the ground. The next six inches were composed of a series of alternate layers of hard, impervious ice (K) separated by thin sheets of old snow well packed. One ice-crust was two inches thick, two were one inch each, and two other thin ones completed this series. These crusts remained unaltered until near the first part of April and played an important rôle at the latter part of the season by preventing penetration of melt-water. The temperature below these crusts was 29° and above them it was 28°. Above these laminated ice-layers were eight inches of snow of irregular crystals and a two-inch crust (L), the upper half being very hard, impervious, and difficult to break through. This crust remained impervious

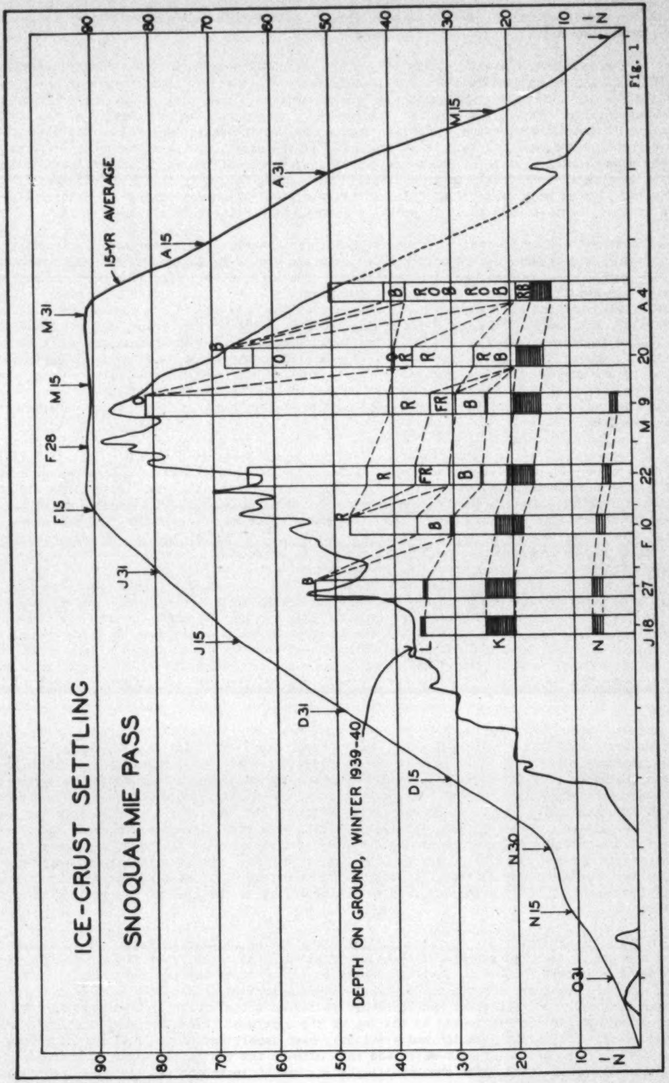

ICE-CRUST SETTLING
SNOQUALMIE PASS
15-YR AVERAGE
DEPTH ON GROUND, WINTER 1939-40
O31
N15
N30
D15
D31
J15
J31
F15
F28
M15
M31
A15
A31
M15
90
80
70
60
50
40
30
20
10
-N
J 18
27
F
10
22
M
9
20
A 4
L
K
N
B
R
FR
O
RR

Fig. 1

until the middle of March, as will be seen later. At the time this observation was made the air-temperature was 20° F.

Little snow fell between January 18 and 25, but on January 26 a 16-inch fall increased the depth to 53 inches on January 27. On this date the profile showed that changes in the snow below the 35-inch line were practically nil, for no settling or melting had occurred during the nine-day interim. The cold weather of January 18 to 23 lowered the temperature of the whole column. It was 31° at the top, 26° at 45 inches, 23° at 35 inches, and 29° at the bottom. These low temperatures also had an effect on the newly fallen snow, for there was little deformation of the snow-crystals. A thin, porous rain-crust had formed at the surface, but later it had no effect on penetration of melt-water. A bottle of bluing, cooled in the snow, was sprinkled over the surface--just back from the profile--after this examination was completed. The precipitation (melted) from January 18 to 21 was 2.53 inches, all in the form of snow.

Though a total of 20 inches of snow fell between January 27 and February 10, melting, evaporation, and packing had reduced the depth on the ground to 47 inches, far less than average (85 inches, 15-year average) for this date. The profile (see Fig. 1) showed the bottom crust N was about two inches lower and the thick crusts K had also settled two inches. Above these crusts settling was somewhat more pronounced. The hard crust L, which was at 35 inches on January 27, was now at 30 inches. The bluing had penetrated to this layer, but not below it; the bluing occupied a layer six inches thick indicating that the top of the snow which was at 53 inches on January 27 was now at 36 inches. The new 20 inches of snow had formed a layer but 11 inches in thickness. Rain and snow amounting to 8.67 inches (melted) had fallen in the 14 days preceding the 10th. The temperature had risen markedly; from the thick crusts to the top it was 31° and was 30° at the bottom. A bottle of cooled red liquid dye was sprinkled over the surface before leaving.

On February 22 the depth on the ground had increased to 64 inches (approximately 91 inches, 15-year average) as a result of two heavy snowfalls on February 12 and 16. Examination of the profile showed that layer N had settled about two inches and was only two inches from the ground. The thick crusts K had also settled the same amount with the top now at 21 inches above the ground. The vertical thickness of crusts K now amounted to but five inches, the decrease being partly due to the compacting of the old snow separating the ice-layers. At 25 1/2 inches was the bottom of the blue layer which 12 days ago was at 30 inches. Layer L continued to prevent any downward percolation from above it. Faint red was detected just above the blue layer showing that some, albeit little, melt-water had penetrated that far. However, this faint red changed abruptly to prominent red at 36 inches and continued so up to 45 inches. This showed that that part of the column had settled about two inches. Cold weather had again changed the temperature of the top half of the column, for it was two to three degrees colder than on February 10. Several thin crusts had developed within the newly fallen snow, but they had no effect on the downward motion of melt-water. Though 36 inches of snow had fallen in the past 12 days, this amount had increased the depth but 20 inches. The precipitation from February 10 to 22 formed 3.95 inches of water.

Between February 22 and March 9, when the Pass was next visited, a total of 89 inches fell. This amount brought the total depth to 82 inches (approximately 92 inches, 15-year average). The melted precipitation during these 16 days was 13.18 inches. In spite of the increased overburden, the lower part of the column settled only two inches again, as was evidenced by the top of the K crusts being at 19 inches. Layer N could not be distinguished. Either melting had changed its character or it had been completely melted. The character of the snow in the bottom part of the column had not changed, for the particles were still irregular in shape and of clear ice. The sub-freezing temperature of the cover had not allowed the bluing to penetrate any closer to the thick crusts (K) during the interim of 16 days. The snow in the red layer had settled the same amount as in the blue layer. The temperature of the whole column had risen; it was isothermal at 31°. Orange dye was sprinkled on top of the snow at the completion of the examination.

On March 20 another visit was made. In the intervening 11 days only six inches of snow had fallen and the weather had averaged well above freezing. The total precipitation from March 9 to 20 was 1.48 inches (melted). Settling continued in the lower part of the column, but the amount was only one inch, for the top of crusts K was approximately 18 inches above the ground. Evidence that rain and melt-water had descended as far as these crusts is presented in that both the blue and red dye had penetrated to the top of the uppermost layer of these identifying series of crusts. The thin crust L, which had previously been impervious to the bluing, had become porous and downward motion of melt-water and rain allowed the red and blue dye to impregnate a layer some 22 inches thick. The absorbent layer was now 50 inches thick, from the top of the snow (68 inches, to the 18-inch level). The top of the blue had dropped from 29 to 27 inches, and the top of the red had settled two inches to 39 inches. The decrease in thickness of the snow above the red layer was much more than that below it. On March 9 the relatively new snow was some 40 inches thick, but on March 20 it was but 25 inches thick. The orange dye had colored a layer 27 inches thick, the top of which was at 64 inches and the bottom was at 37 inches, or two inches below the top of the red. This leads one to conclude that the whole column above the thick crusts had become quite porous, that all of the thin crusts above 19 inches had lost their impervious character, and that melt-water and rain could easily pass down through at least two-thirds of the column. From the top at 68 inches (approximately 92 inches, 15-year average) to the 50-inch level, the temperature was 32° and below that it was 31° to the ground. At the conclusion of this examination, a bottle of bluing was sprinkled over the top of the snow.

On April 4 the last visit was made. Only two inches of snow had fallen which, together with rain, formed a total of 3.45 inches (melted) for the past 15 days. However, warm weather, evaporation, and rain had reduced the total depth to 51 inches (approximately 87 inches, 15-year average). Crusts K had again settled about two inches with the bottom at 13 inches, and these crusts had been reduced in thickness by melting. However, they still maintained their impervious character, for no coloring had penetrated them. The original red, sprinkled on the top on February 10, had not seeped through the crusts. The top of the blue layer was only 42 inches above the ground and the top of the orange was at 38 inches, leaving a four-inch thickness where there was only blue. The bottom of the blue was on the top of the crusts K. Downward penetration of melt-water and rain had been very rapid during the past two weeks.

Examination of the snow-particles below the thick crusts showed the crystals to be irregular in shape and of clear, transparent ice, and the size of the individual grains to be between 0.3 and 0.4 cm.

No further examination of the profile was made after this date. The depth on the ground decreased rapidly, for on April 15 only 34 inches remained (approximately 71 inches, 15-year average), and the cover was completely gone before the middle of May.

Some conclusions may be reached from this series of observations. The snowfall was subnormal this past winter season. This may be attributed to stronger circulation than normal. It also resulted in a much higher winter temperature with more of the precipitation in the form of rain. After the fourth week of January, the temperature averaged well above freezing. Only two well-defined cold periods occurred during the winter and these were productive of impervious crusts. The temperature was close to the melting point nearly all winter, the snow that fell was wet, the depth on the ground was much less than average throughout the season, and no important crusts developed after January.

Lowering of the ice-crusts of the bottom half of the column seems to be caused, in a large measure, by melting from below in addition to increase of density. This is shown by the even decrease in height of the crusts with time, regardless of the amount of overburden, and because the crusts did not sink appreciably when the column had a temperature well below freezing. The distance between crusts K and N remained nearly constant from January 18 through February 22, and the thickness of the undyed layer just above crusts K also remained quite constant from February 10 through March 9. The lowering of the bottom part of the column, therefore, cannot be accounted for by increase of density. The rate of descent of the various identifying crusts and the penetration of dyes suggest that during the period when the winter is well settled the influence of air-temperature, rain, and other atmospheric elements is rather strictly limited to the upper half of the column. Toward the end of the snow-season the structure of the whole cover is affected by the atmosphere more than by the surface on which the snow rests.

The penetration of water, whether it be melt-water or rain, was slow during the main winter season when the temperature of the column was just above freezing, though the liquid easily passed through a number of minor crusts. Some thin crusts, for example, crust L, which are impervious to downward motion are of great importance. The thin crusts, if they remain impervious sufficiently long, become lubricated planes along which the snow may slide. However, the time-interval between the formation of impervious crusts K and L and the accumulation of a deep snow-cover above these crusts was sufficient to permit the formation of a good bond. This is partly responsible for the few avalanches this winter at the altitude where conditions at Snoqualmie Pass may be typical. Lubrication above crust L sufficient to permit slides did not occur until late in the season when the amount of cover above the crust was greatly reduced in thickness.

University of Washington,
Seattle, Washington

DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--Snoqualmie Pass is strategically located for study of water-supplies as in the Yakima Basin, and for investigation of flood-potentiality, as at Mount Rainier. The valuable study in snow-physics made by Dr. Church with few instruments is an abundant promise of further research when weighing instruments have been supplied. The Division of Irrigation and the Weather Bureau will be only too willing to supply the necessary sampler. Recording soil- or snow-thermometers will be valuable supplements.

SNOW-TYPES MET IN HIGHWAY SNOW-REMOVAL

J. D. MacVicar

(Note: Prepared and presented by Mr. MacVicar in the absence in Alaska of Lacey V. Murrow, Director of Washington Highways. This paper represents the progress made in the study of the physics of highway snow since the series on snow-removal was presented by the States of California, Oregon, and Washington at the Edinburgh Meeting of the International Commission of Snow in 1936 [see Bull. No. 23, Internat. Assoc. Sci. Hydrol., 1938, pp. 439-480].)

Due to variable climatic conditions that are encountered in different sections of the State of Washington, there are different types of snow, each characteristic of locality and the winds and weather that are dominant in that locality.

West of the Cascade Range of mountains, where the prevailing winds are westerly from off the Pacific Ocean and more or less tempered as to the degree of their severity, the snow that falls is quite generally moisture-laden to a much greater extent than that which is encountered in regions east of the mountains where the prevailing winds are more northerly and easterly. Coupled with these northerly and easterly winds we get temperatures varying from 0° F to as much as 25° and 30° below.

Highway-department records covering the months of January and February, 1940, indicate that on 29 days of these 60, it was snowing in Snoqualmie Pass at 8 a.m. The maximum temperature recorded on these 29 days was +34° F and the minimum was +13°. The average temperature was 28°. The total depth of new snow that fell was 114 inches, and the depth of compacted snow on the ground at the end of the period was 82 inches.

In the same period, the records indicate that at Spokane it was snowing on 16 days and that the maximum temperature was +38° F and the minimum 16°. The average temperature was the same as at Snoqualmie Pass, namely, 28°. The total depth of new snow that fell was 24 inches, and there was remaining on the ground at the end of the period only patches of snow. Bare ground as thus recorded is not altogether indicative of any melting that had occurred but rather of drifting, which is a prevalent condition that usually follows in the wake of, or occurs during progress of, snow-storms in this part of the country.

Snow that usually falls in the Spokane Area is of a drier nature than that which falls in Snoqualmie Pass and is very susceptible to drifting under conditions of only moderate winds.

Records at Spokane covering the months of December, January, and February in winters from 1937 to 1940 indicate as follows:

1936-37--Total snowfall 62.3 inches; water-content 3.68 inches; ratio 16.9 inches snow to one inch water.
1937-38--Total snowfall 41.0 inches; water-content 3.23 inches; ratio 12.7 inches snow to one inch water.
1938-39--Total snowfall 42.7 inches; water-content 3.76 inches; ratio 11.35 inches snow to one inch water.
1939-40--Total snowfall 24.0 inches; water-content 2.33 inches; ratio 10.0 inches snow to one inch water.

More or less superficial studies made in the Spokane Area indicate that snow falling at average temperatures of from +15° to +30° F give a water-content in ratio of about ten to one, while snows falling at temperatures of from +30° to +38° F give a water-content in ratio of about five or six to one. The amount of this latter type of snow, however, is quite small in the Spokane Area where, as before stated, winter temperatures sometimes reach as low as -30° F.

At Snoqualmie Pass, which is a Cascade Mountain Range Area, the record of snow as concerns its water-content has been kept by a different method than at Spokane, namely, on a weight-per-cubic-foot basis. We find that the average weight of snow as it falls is approximately 6.25 pounds per cubic foot and with a water-content of ten per cent. When compected to the extent as when moved to the side of the road by push-plows and rotaries, its weight increases to 29 1/2 pounds per cubic foot and the water-content increases to 46 per cent. It has been found, too, that in localities not affected by avalanches or slides, and where both rains and freezing temperatures occur, the average weight per cubic foot reaches about 40 3/4 pounds and the water-content reaches as high as 64 per cent.

Generally speaking, all snows that fall on the west slope of the Cascade Mountains are of a wet, large, flaky, and soft variety, though at or near the summits in highway-passes, the texture changes somewhat and becomes finer and granular to an extent that it drifts quite readily.

At Stevens Pass, which is in the Cascades and northerly of Snoqualmie, the snowfall in the winter of 1938-39 amounted to 294 inches with a water-equivalent of 24.80 inches. This would be a ratio of 11.8 inches of snow to one inch of water. In the winter of 1939-40 the total snowfall in Stevens Pass was 146 inches and the water-equivalent was 16.79 inches, or a ratio of 8.71 inches of snow to one inch of water. These records indicate that the weight of snow in 1939-40 was 1.36 times greater than in 1938-39. It is known, too, that snowfall of this year was all at much higher temperatures than in 1938-39, though the thermometer-record in Stevens Pass is not available.

Records made by the National Park Service in Paradise Valley (elevation 5,500 feet) in January, 1940, indicate that 14 inches of snow was equivalent to 1.43 inches of water, which would be a ratio of ten to one the same as recorded by the Highway Department at Spokane.

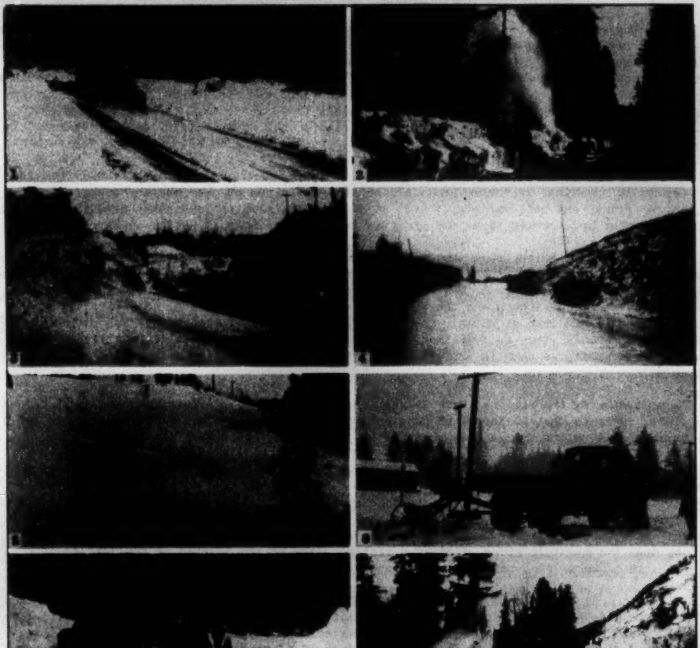
Along the Columbia River in southern Washington, where the terrain rises abruptly above the River, there develops a type of snow not known to other sections and which is commonly called "tapioca." This type of snow forms in crystals similar to the food-product, tapioca, and unlike hail is a globule of snow rather than of ice and is therefore much lighter. This so-called "tapioca"-snow falls upon the mountain-sides and seldom comes to rest where it falls but rolls or flows down the mountain-sides, finding a resting place on the highway or railroad that occupies the more or less level terrain at the foot of cliffs that border the Columbia River.

Other types of snow common to this Columbia River Area consist of, first, a heavy wet snow of such large water-content that it will not compact under traffic. This type of snowfall does not usually occur in great depths. However, it may cover a large area and its removal during the storm-period is very important as a slight change of temperature downwards will cause this wet slush to freeze on the pavement and will create a condition making travel on the highway practically impossible. An illustration of this condition is seen in views 1 and 2 of the accompanying plate. A second type of precipitation that causes great inconvenience on the highways, and which is peculiar only to this Columbia River Area, is brought about by high-velocity northwesterly winds during rain-storms, when the temperature is approximately at the freezing point. In storms of this kind it is not uncommon for ice to form to a depth of two or more inches on the highways in just a few minutes and also on trees and fence-posts, always on the side from which the wind is approaching. Because of wind-conditions and the slippery condition of pavements, it becomes impossible for traffic to move until the road-surface is striated and thereafter the grooves filled with sand or other abrasives. Sand or abrasives applied in advance of striating the icy surface are blown off as fast as they are applied. Views 3 and 4 illustrate the condition above described and some results to traffic that attempted negotiation of the icy surface before treatment.

Another type of snow peculiar to the Columbia River Area is so dry and fine in particles as to resist the usual effect of snow-fences. This type of snow will not compact and moves back and forth and sideways, all in accordance with any slight variation of the winds. View 5 illustrates a cut filled with snow of this type.

A brief description of some methods of snow-removal and a few views that are illustrative may be of interest and are now offered. View 6 illustrates the somewhat primitive type of equipment that was used in 1921 before there was ever any attempt made to keep open highways crossing the mountains. View 7 is of a steam-shovel, burning coal for steam-purposes, that was used to open up Snoqualmie Pass in 1923, which was the first time that that operation was attempted.

An up-to-the-minute rotary snow-plow, such as in view 8, is used for the keeping open of those mountain passes that give access between the west coast and eastern Washington. These



Views of snow-types on Washington highways and methods of snow-removal

[(1,2) Heavy, wet snow that will not compact under traffic; (3,4) ice on pavements; (5) dry drift-snow; (6) primitive snow-removal equipment of 1921; (7) coal-burning steam-shovel, Snoqualmie Pass, 1923; (8) up-to-the minute rotary snow-plow; (9,10,11) removal of snowslides--(9,10) Big Bertha snowslide February 29, 1940; (12) complete operation in opening up section of Chinook Pass, allowed each winter to close up entirely] rotary snow-plows are fully radio-equipped and afford constant communication between the snow-fighting forces and their headquarters, as also the outside world at large. The State of Washington owns 18 units of this type of equipment, each of which represents an investment of about $15,000.

Views 9 to 11 are of slides taken before and after. View 12 depicts the complete operation of opening up a section of Chinook Pass, which is allowed each winter to close up entirely. In the spring the usual average depth of snow is about 20 feet. It is quite solidly compacted and to such extent that a gas-power shovel equipped with caterpillar-crawlers leads the way and removes a top course equivalent to about ten feet. Following this comes a caterpillar-tractor with bulldozer-attachment. This bulldozer is used to push back the bottom bench to level of the grade of highway where the loosened snow is picked up by the rotary snow-plow and blown out and over the sides of the trench that results from the operation as a whole. Note the claw-like arm that extends out in front of the rotary plow. This claw is used for breaking and pulling down the high sides of the trench when the operation of widening out for two-way traffic is undertaken. The first operation above described gives only a one-way road and this is always widened out before the highway is thrown open to traffic.

Department of Highways, State of Washington,
Olympia, Washington

JOINT MEETING WITH THE SECTION OF HYDROLOGY OF THE AMERICAN GEOPHYSICAL UNION AND THE AMERICAN METEOROLOGICAL SOCIETY

FLOODS

Phil E. Church, Merrill Bernard, and J. Cecil Alter, presiding

FORMATION OF SNOW-CRYSTALS ON THE MOUNTAINS AND IN THE LABORATORY OF JAPAN: A SOUND FILM

Ukitiro Nakaya

The sound-film on "Formation of snow-crystals on the mountains and in the laboratory of Japan" by Ukitiro Nakaya, Professor of Physics, Imperial University of Hokkaido, Sapporo, Japan, was presented during a joint luncheon. [The "Voice-commentary" accompanying this film appears in Trans. Amer. Geophys. Union, 1940, pp. 97-98, in connection with the Stanford Meeting.]

The film has been shown ten times at colleges and meteorological seminars throughout the United States in accordance with the terms of gift by the Hokkaido University and the author to the International Commission of Snow. By reason of the excellent reproduction-apparatus of the Egyptian Theatre, the film was unusually impressive.

FORECASTING OF STREAM-FLOW FROM MELTING SNOW

Merrill Bernard

The forecasting of stream-flow from melting snow was discussed informally in connection with the mountain-snowfall program. Presentation of a formal paper was deferred because "matters in the field covered by the topic are developing so rapidly that I have decided to withhold discussion until 1941."

U. S. Weather Bureau,
Washington, D. C.

SOME FACTORS AFFECTING FROST-PENETRATION

H. B. Atkinson and Clyde E. Bay
(Presented by J. E. Church)

Starting with the winter of 1936-37, measurements have been made to determine the penetration of frost under different farming practices, exposures, and cover-conditions. The data were collected on the Upper Mississippi Valley Conservation Experiment Station, located at La Crosse, Wisconsin, which is about 43°.5 north latitude. The soil-types, on which the studies were made, are the Clinton Silt Loam, which has a four- to six-foot loessial deposit over soil residual limestone, and the Dubuque Silt Loam, which has a 12- to 24-inch loessial deposit over soil residual limestone.

The measurements of frost-depth were obtained by the use of a King soil-tube and hammer. After measuring snow-depth, the tube was driven into the soil-profile, a few inches at a time. The core-samples were removed and examined for ice-crystals. The depth to which these crystals occurred was recorded as the frost-depth. Three measurements were usually taken on each plot.

Some of the factors which have been found to affect frost-penetration and condition of frost are snow-depth, vegetal cover, atmospheric temperature, and exposure. Other factors which probably have an appreciable influence, but have not yet been closely studied, are initial soil-temperature, moisture-content of soil, soil-type, snow-density, and organic-matter content of soil.

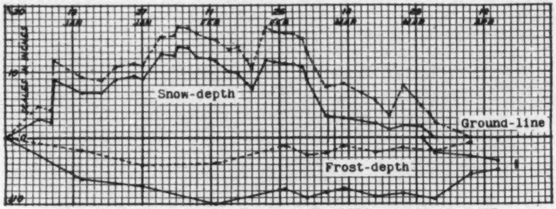


Fig. 1--North exposure, December 28, 1936 - April 26, 1937
Ungrazed woodlot ----- Open bluegrass pasture ——

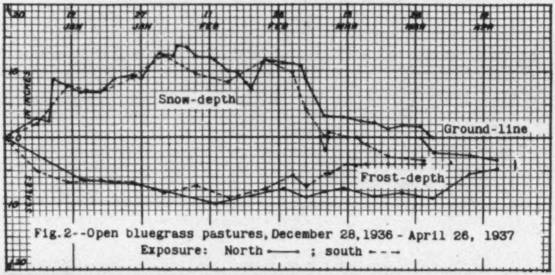


Fig.2--Open bluegrass pastures, December 28, 1936 - April 26, 1937
Exposure: North —— ; south ---

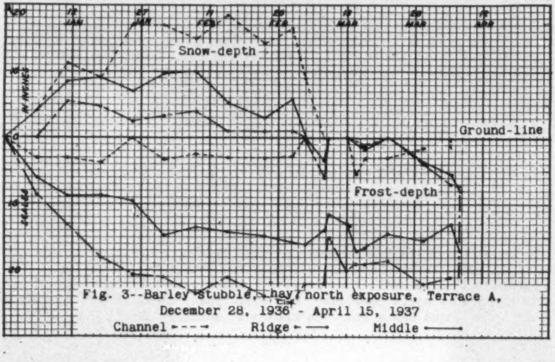


Fig. 3--Barley stubble, hay, north exposure, Terrace A, December 28, 1936 - April 15, 1937
Channel ---- Ridge -— Middle ——

Graphs are included with this report which show depths of snow-mantle and depths of frost-penetration at the time of measurement for each plot studied. Sufficient measurements were not taken to show the exact time all frost had thawed. This last measurement is, of course, the one where the frost has completely left the ground, and in most cases is preceded by a period of thawing from both the surface and the lower frost-line. Therefore, the exact point at which the frost left the ground is not shown. In order to avoid any misinterpretation a perpendicular line of the same type used to denote the particular area or cover-condition was used to indicate the date on which there was no frost in the soil. The position of these lines indicate the limits within which the frost disappeared from the soil-profile.

The effect of snow-cover on frost-penetration is indicated [see 1 of "References" at end of paper] in Figures 1 and 3. In Figure 1, it can be seen that the snow-depth remained deeper in

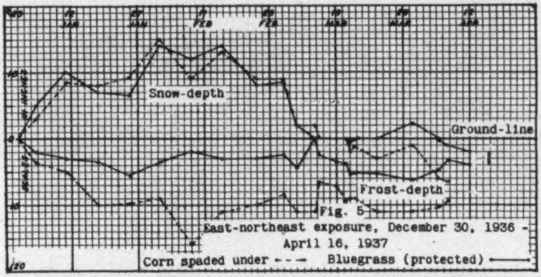


Fig. 5--East-northeast exposure, December 30, 1936 - April 16, 1937
Corn spaded under - - - Bluegrass (protected) ——

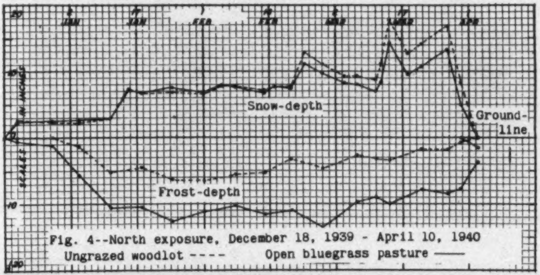


Fig. 4--North exposure, December 18, 1939 - April 10, 1940
Ungrazed woodlot ---- Open bluegrass pasture ——

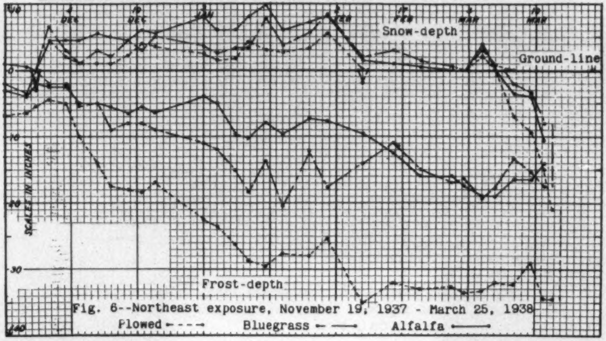


Fig. 6--Northeast exposure, November 19, 1937 - March 25, 1938
Plowed - - - Bluegrass — — Alfalfa ——

the woodlot than in the open pasture during the winter season. However, it must be conceded that there is also a 1 1/2-inch depth of litter on the woodlot. Figure 3 shows the snow- and frost-depths in a terraced field with a north exposure, as measured during the winter of 1936-37. Measurements were made on the terrace-ridge, in the terrace-channel, and on the middle or undisturbed area between the terraces. There was, of course, a greater deposition of snow in the terrace-channel and less on the terrace-ridge.

In this case, variation in frost-depths can be largely attributed to the difference in the depth of the snow-mantle, as the vegetal cover (grain-stubble) was the same on all three loca-

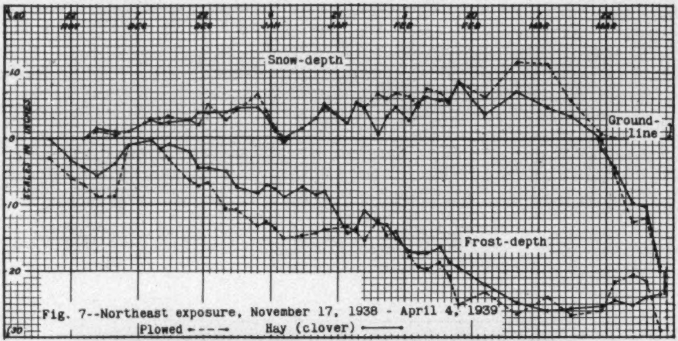


Fig. 7--Northeast exposure, November 17, 1938 - April 4, 1939

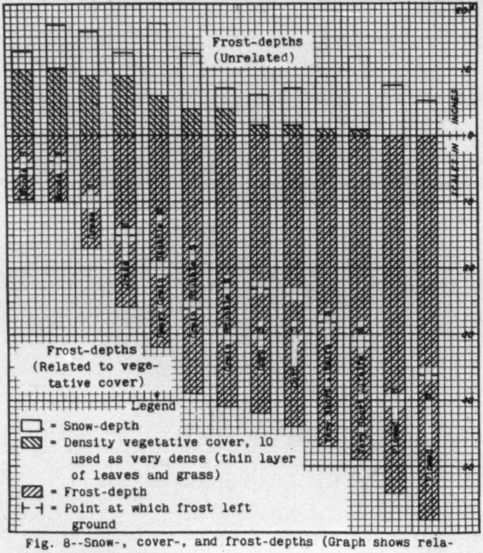


Fig. 8--Snow-, cover-, and frost-depths (Graph shows relation of frost-depths to vegetative cover; north exposed slopes frozen slightly more) tions and all had the same exposure. However, it must be recognized that variations exist in moisture-content, depth of surface-soil, and organic-matter content between these locations. The frost was much deeper and the snow-cover was less on the ridge than on either of the other two.

A case-study was made of all available snow-cover and frost-depth data to determine the effect of depths of snow on change in frost-penetration within plots. (The influence of atmospheric temperature was not considered.) It was found that where there were ten inches or more of snow the depth of frost decreased in 15 out of 23 cases. Where there were less than ten inches of snow the frost-depth increased 127 times in 188 cases. In making this study only measurements made where there actually was snow on the ground were considered. No measurements were considered after the first complete disappearance of snow in the spring. Where there were ten or more inches of snow the frost decreased in depth approximately two times out of three, but where there were less than ten inches of snow this ratio was reversed and the frost decreased in depth only one time out of three.

To test the effect of snow-cover further, a plowed field with a north exposure was covered with straw before frost began to penetrate the soil during the winter of 1939-40. When sufficient snow had fallen, the straw was removed, and duplicate plots were covered with six-inch, 12-inch, and 24-inch snow-depths. There were also two plots which were kept free of snow during

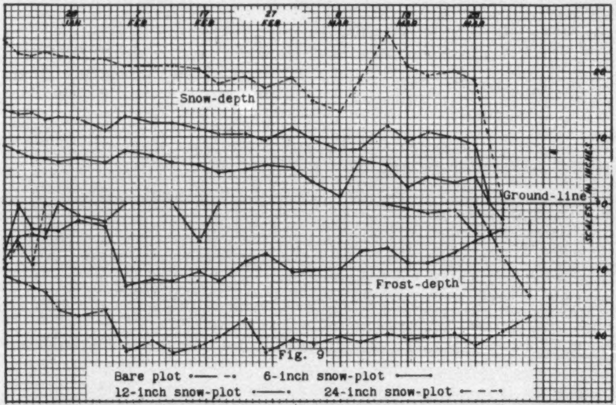


Fig. 9

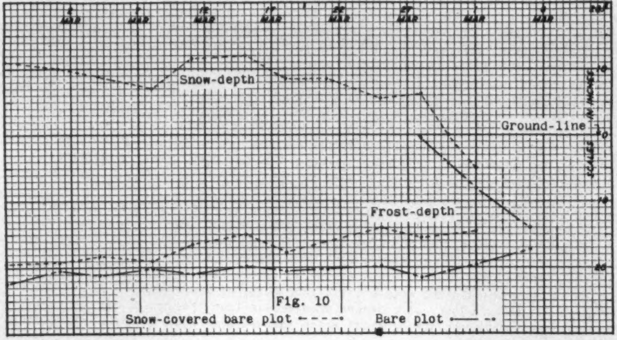


Fig. 10

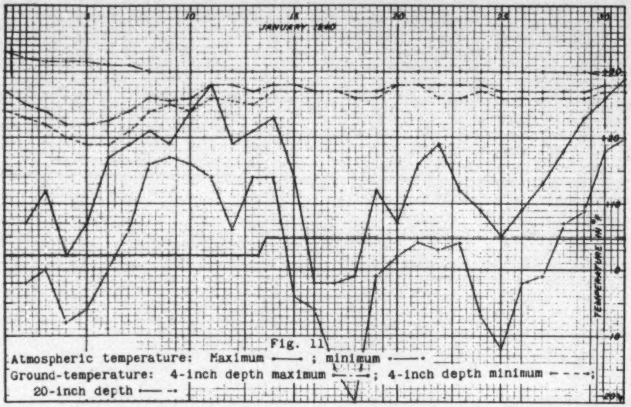


Fig. 11

Atmospheric temperature: Maximum ——• ; minimum •——•

Ground-temperature: 4-inch depth maximum –·–·–; 4-inch depth minimum – – – –;
20-inch depth •—— ––

the frost-period. The plots were covered by sifting the snow through a quarter-inch meshed screen, allowing it to fall on the plot-areas. The snow was very fine and packed considerably. Snow-cores were taken to determine the density of the snow covering the plots. The densities (moisture-contents per inch of snow) of snow-covering plots were 0.256 inch, 0.246 inch, and 0.247 inch for the six-inch, 12-inch, and 24-inch snow-covers, respectively. It can be seen from the densities that the snow was more than twice that of normal snowfall.

Figure 9 gives a picture of what took place under the different snow-depths during the frost-period. Measurements during the first ten days indicate the presence of frost under the three different snow-depths and the bare plot. The frost disappeared from the 12-inch and 24-inch plots, but continued to deepen on the six-inch and bare plots. There were a few instances in later measurements indicating the presence of frost under the 12-inch snow-cover. The snow settled to some extent on the plots and warm weather during the first week of March caused some thawing of the snow. It was necessary to add more snow to build the plots up to the original levels. The bare plot was swept clean of snow as soon as possible after each snowfall. That thawing may take place at the lower frost-line as well as at the surface was quite definitely indicated on the six-inch and bare plots, beginning March 25 and April 1, respectively.

The two bare plots used in the snow-depth experiment quite consistently maintained the same frost-depth and so one of them (Fig. 10) was covered with a 12-inch depth of snow on February 26 and frost-measurements were continued. This was done to determine whether a 12-inch depth of snow would have sufficient insulating value so that the frost could be drawn from the soil by warmth of the Earth. Within a few days the frost in the newly covered plot softened considerably and less difficulty was encountered in driving the soil-tube into the frozen soil than on the bare plot where the frost was extremely hard. Figure 10 shows what took place under the bare and newly covered plots. Along with the softening of the frost there was a gradual rise toward the surface of the lower frost-line on the snow-covered area while that on the bare plot maintained very nearly the same frost-depth until the first of April when it began to rise.

Snow, when of sufficient depth, will protect the soil against frost if the snow covers the area before frost has a chance to penetrate the soil. It has been found that if frost does penetrate the soil and snowfall of sufficient depth follows, frost may be drawn from the soil.

Vegetation is a factor in frost-penetration and its effect is dependent upon the type and density of the vegetal cover. The vegetation acts as an insulator and prevents the rapid lowering of soil-temperatures which take place in open plowed areas. The effects of vegetation are shown in Figures 1, 5, 6, and 7. In Figure 1 [1], an ungrazed woodlot is compared with an open bluegrass-pasture. Both areas have a north exposure. There is a dense sod in the open pasture and the woodlot is a hardwood-stand with a 1 1/2-inch cover of leaf-litter. During the winter of 1936-37, the protected woodlot had a deeper snow-mantle than the open bluegrass-pasture area. The woodlot was less affected by strong winds which removed some snow from the open-pasture area.

Table 1--Daily official temperature-record at Menomonie, Wisconsin, November 1, 1935, to April 30, 1936

[A severely cold winter, with the ground covered with a comparatively light snow-blanket until February, resulted in unusual depths of freezing]

Date	Low	High	Date	Low	High	Date	Low	High
1935	°F	°F	1936	°F	°F	1936	°F	°F
Nov 1	26	34	Jan 1	33	38	Mar 1	18	30
2	28	35	2	34	36	2	19	34
3	38	40	3	15	37	3	15	41
4	25	35	4	8	15	4	- 1	26
5	20	29	5	8	21	5	- 3	5
6	20	40	6	- 2	28	6	4	16
7	30	45	7	11	17	7	16	34
8	30	46	8	18	28	8	30	32
9	37	50	9	0	27	9	30	40
10	23	42	10	- 2	23	10	32	46
11	22	32	11	20	33	11	20	34
12	28	39	12	1	24	12	12	24
13	32	44	13	0	18	13	12	25
14	37	40	14	8	23	14	22	31
15	35	36	15	- 1	18	15	26	32
16	32	36	16	8	16	16	21	36
17	35	38	17	2	18	17	20	32
18	38	40	18	- 9	6	18	26	40
19	26	40	19	-17	4	19	23	40
20	22	36	20	-17	4	20	24	46
21	17	20	21	-32	- 1	21	31	36
22	16	24	22	-34	-24	22	36	42
23	17	38	23	-32	-20	23	36	44
24	30	45	24	-30	-13	24	22	43
25	29	40	25	-20	- 2	25	24	32
26	31	36	26	-22	- 5	26	24	32
27	20	38	27	-18	- 3	27	20	32
28	13	18	28	-18	8	28	19	52
29	12	32	29	- 7	2	29	18	26
30	13	36	30	-16	- 2	30	12	22
Dec 1	9	12	31	-18	0	31	11	22
2	9	32	Feb 1	-21	- 5	Apr 1	20	28
3	8	26	2	-21	4	2	16	28
4	9	28	3	-12	8	3	17	27
5	24	31	4	-24	- 4	4	22	29
6	30	38	5	-24	-12	5	12	33
7	34	41	6	-29	-10	6	7	37
8	32	34	7	-25	14	7	7	28
9	12	34	8	- 7	22	8	28	38
10	0	12	9	-13	6	9	34	45
11	14	24	10	-14	- 1	10	34	48
12	26	33	11	-14	- 3	11	34	52
13	33	38	12	- 9	1	12	30	45
14	33	38	13	-17	14	13	33	52
15	30	38	14	-20	-11	14	39	52
16	21	34	15	-38	-12	15	35	47
17	23	30	16	-38	-16	16	31	44
18	16	28	17	-20	-12	17	30	46
19	- 5	14	18	-20	- 4	18	30	50
20	- 6	2	19	-17	2	19	41	68
21	1	16	20	-23	7	20	26	46
22	19	21	21	-24	5	21	26	40
23	5	22	22	-25	12	22	28	50
24	4	19	23	12	34	23	30	46
25	- 7	19	24	20	37	24	34	42
26	- 8	4	25	18	27	25	34	53
27	- 2	10	26	9	27	26	37	59
28	0	16	27	- 2	14	27	40	54
29	13	22	28	5	28	28	40	72
30	22	26	29	5	19	29	42	54
31	27	33				30	40	50

Frost-depths were much less in the woodlot due to the deeper snow-cover and the protection afforded by the leaf-litter. During the winter of 1939-40 (Fig. 4 [1]), snow-depths were practically the same on both areas for the first part of the winter. During this same period the frost-depth in the open-pasture area was approximately twice as deep as in the protected woodlot-area. This clearly illustrates the excellent insulating value afforded by leaf-litter found in protected woodlots.

Frost-depths in plowed areas during this period averaged 25 inches or about five times that in the protected woodlot. During cold periods, where there is not a blanket of snow covering the soil-surface, frost penetrates the plowed soil much more rapidly than it does in places that are densely vegetated (Figs. 1, 6, and 7).

Between the two extremes of plowed and protected woodlot-areas, there are the grazed woodlots, open pastures, alfalfa, clover-timothy hay, grain- and corn-stubble. These different types of cover have been found to retain a varying mantle of snow, depending upon the density and height of the vegetation.

The winter of 1935-36 was very cold and there was little snow on the ground until February. Data recorded on the Menomonie, Wisconsin, Project during March 1936 indicate the unusual depths of freezing under different cover- and exposure-conditions (Fig. 8 [2]). The winter of 1936-37 was quite cold but early and lasting snow protected the soil against deep frost-action (Fig. 5). During the winter of 1937-38, the temperatures were not extremely cold, but there was little snow and as a result frost penetrated the soil to depths of 35 inches (Fig. 6). The winter of 1938-39 was quite mild until February when 15 days of sub-zero weather caused the frost to penetrate as deep as 26 inches (Fig. 7). The 1939-40 winter had about two and a half weeks of sub-zero weather, mostly during the first and latter part of January. Snow-cover was not very great and frost penetrated to slightly more than two-foot depths.

Table 2-A--Snow- and frost-depth readings, 1936-37

Date	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches
	Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line	
1936	Watershed B			Watershed G		
Dec 7	....	....	5.72	....	....	3.08
15	....	....	4.28	....	....	2.65
17	....	....	T	....	....	T
1937						
Jan 4	....	....	4.90	....	....	2.92
7	....	....	4.22	....	....	2.40
8	....	....	11.65	....	....	8.85
14	....	1.85	9.18	....	6.20	6.80
18	....	....	8.78	....	....	6.85
21	....	....	10.60	....	....	8.90
25	....	....	11.28	....	....	9.35
27	....	4.20	11.00	....	7.25	8.95
31	....	....	15.25	....	....	12.58
Feb 3	....	....	15.40	....	....	12.35
4	....	....	16.78	....	....	13.78
6	....	....	16.75	....	....	13.60
8	....	....	15.70	....	....	12.15
11	....	....	15.02	....	....	12.00
12	....	3.90	14.72	....	10.00	11.62
15	....	....	13.35	....	....	10.00
17	....	....	13.68	....	....	9.82
1937	Watershed B			Watershed G		
Feb 19	....	....	11.78	....	....	8.12
20	....	....	10.38	....	....	7.38
23	....	....	16.62	....	....	11.65
25	....	....	16.02	....	....	11.45
27	....	1.15	15.88	....	7.70	11.18
Mar 1	....	....	15.68	....	....	11.05
3	....	....	15.00	....	....	10.78
4	....	2.60	12.92	....	9.00	8.78
8	....	2.30	7.70	....	8.20	3.25
12	....	1.30	8.05	....	7.60	3.02
16	....	....	6.75	....	....	2.45
19	....	2.20	5.75	....	8.90	2.25
22	....	....	3.40	....	....	1.30
25	....	1.50	7.90	....	8.40	1.80
29	....	....	4.95	....	....	1.70
31	....	....	3.50	....	....	0.50
Apr 1	....	2.00	2.30	2.20	9.10	T
6	....	....	1.00	....	....	T
9	....	0.70	0.00	2.70	5.50	0.00
15	....	0.00	0.00	3.40	4.85	0.00
19	....	0.00	0.00	....	0.00	0.00

[a] Depth of unfrozen soil above frozen soil.

Atmospheric temperature, soil-temperature, and snow-depth records were correlated to show the effect of snow-cover and atmospheric temperatures on soil-temperature. The atmospheric temperatures were recorded on a hygrothermograph and the soil-temperatures were recorded on a thermograph with thermal units located at four inches, 20 inches, and 37.5 inches below the soil-surface of a lysimeter three feet in diameter by 44 inches deep. The lysimeter-plot was fall spaded. The daily maximum and minimum temperatures of the atmosphere and the soil-temperatures at four- and 20-inch levels are indicated for the month of January in Figure 11. During the first two weeks of January there were slightly more than two inches of snow covering the plot. Atmospheric temperatures were quite low during the first week and notable daily temperature-changes took place in the soil at the four-inch level. New snow falling on January 13 and 14 increased the cover to approximately five inches. Considerably colder atmospheric temperatures followed, reaching -20° F on January 18. Under the five-inch snow-cover there was less change in soil-temperature at -20° F than there was under the two-inch snow-cover at -8°, indicating the insulating effect of snow.

Thermometers were placed in contact with the soil under the six-inch, 12-inch, and 24-inch snow-depths on a plowed field. Daily temperature-fluctuations under the six-inch snow-depth amounted to as much as 2° F when the maximum and minimum atmospheric temperatures were 28° and 24°, respectively. The temperatures under the 12-inch and 24-inch plots remained unchanged. A temperature-study was conducted in an alfalfa-field during the winter of 1924-25 by Arny [3]. He placed a thermograph in an alfalfa-field with one thermal unit placed in contact with the soil beneath eight inches of snow-cover. The other thermal unit was placed about two feet above the ground, shaded, but exposed to the air. During a two-weeks period the temperature beneath the snow fluctuated within a degree from day to day except in one case where the atmospheric temperature dropped to -22° F, then the temperature beneath the snow chenged about 3° F.

During the winter of 1935-36 snow- and frost-depth measurements were made on farms located near Menomonie, Wisconsin, by William M. Briggs, Agronomist of the Soil Conservation Service. These data, a portion of which are shown in Figure 8 [2], show the relation of vegetal cover to frost-penetration. Measurements were made on similar sites having a north and a south exposure. During the winter of 1935-36 there was very little snow on the ground until about February 1. From January 18 to February 23 the temperature averaged -12°. The lowest temperature was -38° on February 15 and 16. The fact thet part of this period of sub-zero weather occurred before the ground was covered with a very heavy mantle of snow probably accounts for the great depth to

Table 2-B--Frost- and snow-depth readings, 1937

Date	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches
	Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line	
	Terrace A-4--North exposure									U.P.W.		
1937	Middle			Channel			Ridge			South exposure		
Jan 4	....	6.0	4.0	....	3.0	4.0	....	8.5	0.0	....	5.0	2.0
11	....	8.75	8.5	....	3.0	11.25	....	13.0	5.5	....	6.75	7.75
18	....	8.75	9.0	....	3.75	9.0	....	18.0	4.75	....	6.8	7.10
25	....	9.5	7.0	....	0.0	17.0	....	20.5	2.5	....	6.75	9.0
Feb 1	....	14.75	9.75	....	3.25	17.0	....	21.0	3.25	....	8.25	12.30
8	....	13.5	10.0	....	2.5	15.0	....	23.5	4.0	....	7.25	9.6
15	....	14.25	5.25	....	3.0	18.5	....	21.0	1.0	....	9.0	8.38
23	....	14.75	3.0	....	3.0	14.25	....	23.75	1.0	....	7.75	11.75
Mar 1	....	15.75	5.75	....	2.75	16.5	....	24.75	1.0	....	5.75	9.85
4	....	16.0	0.0	....	0.0	9.0	0.5	22.0	0.0	....	7.35	4.12
8	3.5	10.5	0.0	....	0.0	0.0	6.0	22.0	0.0	2.0	5.5	0.0
9	....	11.5	0.0	....	0.0	0.0	....	15.0	0.0	....	5.5	0.75
13	....	13.0	0.0	....	0.0	0.0	....	20.0	0.0	....	4.0	0.0
15	....	17.0	0.0	0.5	5.5	0.0	....	19.0	0.0	....	4.25	0.0
16	1.25	.....	.....	....	....	.....	1.25	.....	....	0.87	.....	.....
17	1.75	16.5	0.0	1.0	3.0	0.0	1.25	19.0	0.0	1.0	4.0	0.0
22	....	14.5	0.0	....	3.0	0.0	....	18.5	0.0	2.87	4.0	0.0
30	3.75	15.5	0.0	....	1.5	0.0	4.0	22.0	0.0	3.5	4.0	0.0
Apr 5	5.5	13.0	0.0	0.0	0.0	0.0	7.0	21.0	0.0	0.0	0.0	0.0
7	8.0	17.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	....	.....	.....
12	0.0	0.0	0.0	....	....	....	....	.....	....	....	.....	.....
	East-northeast exposure											
1937	Plowed corn-stubble			Blue grass (protected)			Clover-hay			Plowed clover-sod		
Jan 4	0	3.5	3.0	0	2.0	5.0	0	6.0	1.75	0	3.5	2.0
11	0	5.0	8.5	0	3.0	10.0	0	11.0	7.5	0	13.0	7.75
18	0	10.0	8.0	0	3.5	7.0	0	10.0	8.0	0	14.0	7.5
25	0	9.75	9.25	0	5.5	6.5	0	12.5	9.25	0	17.0	8.5
Feb 1	0	9.0	15.0	0	3.5	14.0	0	9.0	17.0	0	13.0	11.0
8	0	16.0	9.0	0	2.0	12.0	0	15.5	8.5	0	18.0	8.0
15	0	11.0	13.0	0	3.0	14.0	0	10.5	11.5	0	15.0	10.0
23	0	10.0	9.0	0	3.0	8.0	0	14.0	4.0	0	15.0	2.5
Mar 1	0	8.5	9.0	0	2.5	8.5	0	14.0	4.0	0	16.5	2.0
4	0	11.0	2.0	0	4.5	2.0	0	15.0	0.5	1.0	15.5	0
8	0	11.0	2.0	0	0	0	3.0	10.5	0	3.0	16.0	0
9	0	6.5	2.0	0	2.5	0	0	12.5	0	0	13.25	0
13	0	7.25	0.5	0	3.5	0	0	10.8	0	0	14.8	0
15	0	9.5	0	0	3.75	0	0	11.5	0	0	11.0	0
16	2.0	9.0	0	0.5	4.4	0	1.8	10.05	0	1.75	15.25	0
17	1.25	9.05	0	0.2	5.4	0	1.25	8.25	0	1.5	15.25	0
22	3.0	11.0	0	0	5.25	0	4.25	13.25	0	3.0	15.25	0
30	1.0	11.0	0	0	6.25	2.25	4.0	14.0	0	3.25	19.0	0
Apr 5	6.0	10.25	0	0.25	4.75	0	6.3	9.5	0	5.0	18.25	0
7	6.5	9.5	0	1.0	3.25	0	8.3	11.75	0	5.0	16.0	0
12	0	0	0	2.0	4.0	0	0	0	0	0	0	0

[a] Depth of unfrozen soil above frozen soil.

which the frost penetrated. These measurements were not made throughout the year but were started soon after March 1. The following densities were used for various vegetal covers (10 used as a maximum) and on Figure 8 [2]:

0 = Bare (plowed)
1 = Corn (six-inch stubble, checked) and very short alfalfa-stubble (three inches high, no weeds or grass)
1.5 = Corn drilled
4 = Grain-stubble (four to six inches high)
8 = Good alfalfa- and timothy-stubble
9 = Heavy ungrazed grass-cover
10 = Protected woods

Table 3--Daily maximum and minimum temperatures, degrees Fahrenheit, December 1, 1936, to April 15, 1937

Day	December		January		February		March		April	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	25	9	28	8	2	-16	38	11	37	33
2	37	1	31	11	18	-15	36	19	39	26
3	33	24	24	4	23	- 5	45	23	32	29
4	13	4	35	- 1	9	2	39	28	35	29
5	26	4	25	- 9	22	- 8			39	32
6	- 1	- 3	32	- 9	11	- 3			50	31
7	12	-15	15	5	25	- 3	41	31	48	35
8	26	-10	19	- 2	20	4	24	21	48	35
9	33	10	2	-17	3	-11	17	4	47	31
10	18	15	14	-16	14	-17	21	4	46	29
11	17	-12	23	- 5	35	-12	28	11	56	33
12	33	- 5	26	6	41	11	29	18	51	42
13	35	16	34	8	40	25	25	19	62	46
14	43	21	14	12	21	11	26	12	60	45
15	43	26	4	- 7	23	10	29	15	45	37
16	30	29	27	- 6	33	13	38	20		
17	22	18	27	2	37	15	44	26		
18	28	17	5	-10	43	24	42	28		
19	33	17	22	-12	39	26	40	25		
20	28	18	34	- 8	32	30	34	28		
21	28	19	2	-10	15	13	36	26		
22	31	14	- 2	-15	13	- 7	39	24		
23	45	17	14	-15	13	7	36	26		
24	51	26	18	- 8	9	3	23	23		
25	53	38	6	2	22	3	19	9		
26	53	47	15	-14	23	7	20	5		
27	29	26	33	-12	27	10	32	9		
28	33	21	23	14	23	9	36	16		
29	43	26	29	3			43	25		
30	48	32	29	5			42	30		
31	24	10	5	- 8			44	29		

Frost-measurements have indicated that there may be a greater frost-penetration on north exposures than on south exposures. The data, as indicated by measurements made at the La Crosse Station, have not as yet shown this difference to be very significant. South slopes are exposed to more direct and a longer period of sunlight than the other exposures. As a result, thawing of snow and frost takes place at an early time (Fig. 2).

Usually the thaw-period starts sometime during the last two weeks of March and lasts for a period of time depending upon the conditions of exposure, atmospheric temperatures, and rainfall.

The thaw-periods on plowed areas and the factors affecting their length for 1937-40 are set forth in Table A.

Table A--Thaw-periods on plowed areas, 1937-40

Year	Average temperature		Frost-depth	Thaw-period	Rainfall
	Maximum	Minimum			
	°F	°F	inches	days	inches
1937	38.7	25.6	18.0	27	None
1938	51.1	31.8	34.5	16	1.80
1939	52.7	29.2	26.0	15	None
1940	48.8	38.8	20.0	9	2.00

Alternate freezing and thawing caused by low maximum and minimum daily temperatures and lack of

Table 4--Frost- and snow-depth readings, 1937-38

Date	Northeast exposure								
	Plowed			Grass			Alfalfa		
	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches
	Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line	
1937									
Nov 19	.....	6.75	1.0	....	2.0	1.0	....	3.0	1.0
24	.....	6.5	0.5	....	3.5	0.5	....	4.0	0.5
26	3.0	5.5	0.0	....	0.0	0.0	2.0	2.0	0.0
29	.....	4.5	4.5	....	2.0	6.5	....	2.5	4.5
Dec 3	.....	5.0	2.0	....	2.0	3.0	....	2.5	4.5
6	.....	10.0	1.0	....	5.5	1.0	....	5.0	4.5
10	.....	14.0	1.0	....	5.0	3.0	....	5.0	5.5
13	.....	17.5	1.0	....	9.0	2.0	....	5.5	5.0
17	.....	18.0	2.25	....	8.0	1.5	....	6.5	4.5
20	.....	18.5	4.0	....	8.0	3.0	....	5.5	6.0
23	.....	17.0	3.5	....	9.0	5.0	....	6.5	5.5
1938									
Jan 3	.....	22.5	2.5	....	11.0	3.5	....	4.0	8.0
6	.....	23.5	1.5	....	12.0	2.5	....	5.0	6.0
10	.....	26.25	1.75	....	15.0	3.33	....	9.67	6.0
13	.....	28.6	4.25	....	18.33	3.38	....	10.33	8.0
17	.....	29.5	3.0	....	13.75	7.88	....	8.0	9.88
21	.....	27.66	2.66	....	20.33	3.83	....	9.66	6.0
27	.....	28.0	3.33	....	12.33	5.66	....	7.33	7.16
31	.....	25.33	5.5	....	17.66	8.33	....	7.66	8.17
Feb 8	2.0	35.0	0.0	....	14.0	2.0	....	9.5	1.5
15	.....	32.0	0.0	....	11.0	3.0	....	12.5	1.0
21	.....	33.0	0.0	....	15.0	1.5	....	16.0	0.5
28	.....	32.66	0.0	....	17.0	0.66	....	16.0	0.0
Mar 3	.....	33.66	0.0	....	16.33	0.0	....	17.5	0.0
7	.....	33.33	2.16	....	19.33	3.16	....	19.0	4.0
10	.....	32.0	0.0	....	17.66	0.83	....	19.0	0.0
14	7.0	32.33	0.0	2.0	13.3	0.0	3.5	16.5	0.0
18	9.33	29.0	0.0	3.33	15.33	0.0	4.0	16.5	0.0
21	15.0	34.5	0.0	8.0	17.5	0.0	10.5	14.0	0.0
23	21.0	34.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[a] Depth of unfrozen soil above frozen soil.

rainfall prolonged the thaw-period of 1937 for 27 days. The records of 1938 indicate twice as much frost and a little more than half as long to completely thaw. Much warmer maximum and minimum temperatures and rainfall account for the more rapid disappearance of frost. Although temperatures were not as high in 1940, two inches of rain on April 2 and 3 were very effective in thawing the frozen soil, making the thaw-period the shortest during the four years of record.

With approximately the same length of time required by the thaw-periods of 1938 and 1939 to remove 34.5 and 26 inches of frost, respectively, rain and higher temperatures may account for the more rapid thawing in 1938 than in 1939.

From the erosion-standpoint, soil, especially plowed soil, is very vulnerable to erosion during the periods immedietely after the snow has melted away and the soil-surface begins to thaw. During this period, the plowed layer is in a supersaturated state below which is frozen soil. At times, when the soil is in a completely saturated state, it has a tendency to flow or slide on steep slopes. Intense rains occurring at this time are likely to cause much of the unfrozen soil to be lost. However, drying winds normally change the supersaturated soil to a wet or moist state in a few days. Although moisture-samples have indicated a higher moisture-content in sodded and vegetated areas, the organic matter and grass-roots would hold together the unfrozen portion of the soil and thus prevent the flowing and slipping which occurs on the plowed areas.

Table 5--Frost- and snow-depth readings, northeast exposure, 1938-39

Date	Plowed			Hay		
	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches
	Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line	
1938						
Nov 17	....	3.0	0.0	....	0.0	0.0
22	....	6.0	0.0	....	3.33	0.0
25	....	6.83	0.0	....	4.33	0.0
28	....	8.67	1.0	....	5.66	1.5
Dec 2	....	8.66	0.5	....	3.92	1.0
5	....	1.0	1.0	....	1.0	1.0
10	....	0.33	3.0	....	0.33	2.92
12	....	1.5	3.0	....	1.5	2.16
14	....	3.08	3.33	....	1.0	2.5
19	....	6.33	2.83	....	2.0	2.66
21	....	7.08	2.0	....	4.58	3.92
23	....	6.83	5.0	....	4.58	3.92
27	....	10.5	2.92	....	5.0	4.0
29	....	10.66	4.16	....	7.33	4.5
1939						
Jan 3	....	13.16	6.58	....	8.33	4.66
5	....	12.66	4.0	....	7.0	3.16
7	....	13.66	1.5	....	7.66	1.0
9	0.75	15.08	0.0	0.25	8.91	0.0
13	....	14.66	1.5	....	7.33	1.5
16	....	14.33	3.0	....	8.66	3.0
18	....	13.83	4.66	....	8.0	5.16
1939						
Jan 23	.....	13.33	2.16	.....	14.33	2.16
25	.....	14.0	5.16	.....	13.66	5.33
27	.....	15.33	4.58	.....	11.0	4.75
30	.....	12.33	6.66	.....	12.66	0.5
Feb 1	.....	14.66	6.0	.....	13.0	3.33
3	.....	14.0	6.83	.....	15.0	4.66
6	.....	17.83	6.33	.....	17.0	2.83
8	.....	19.33	4.83	.....	17.33	5.16
10	.....	19.66	7.5	.....	17.33	6.33
13	.....	18.66	7.0	.....	16.33	5.83
15	.....	20.83	5.42	.....	18.66	5.66
17	.....	25.0	8.5	.....	19.33	8.42
23	.....	23.16	6.33	.....	22.0	3.83
Mar 2	.....	26.5	11.5	.....	24.83	7.0
9	.....	24.0	11.16	.....	26.0	4.66
14	.....	26.66	5.66	.....	25.66	3.33
21	0.33	26.0	0.66	1.66	25.33	0.0
24	5.33	21.83	0.0	4.5	24.5	0.0
28	12.66	20.66	0.0	9.83	25.16	0.0
31	12.0	21.66	0.0	10.33	24.0	0.0
Apr 3	19.5	29.0	0.0	20.0	23.5	0.0

[a] Depth of unfrozen soil above frozen soil.

Table 6--Daily maximum and minimum temperatures, degrees Fahrenheit, November 1, 1937, to March 31, 1938

Day	November		December		January		February		March	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	62	39	28	8	15	5	18	-13	52	27
2	32	28	37	14	20	5	30	0	39	27
3	39	16	38	19	27	5	24	15	22	9
4	53	18	25	24	27	12	43	16	23	11
5	40	33	8	1	17	9	37	23	24	17
6	..	33	15	1	10	1	34	31	22	6
7	58	..	20	4	3	- 4	38	22	31	9
8	45	38	9	4	7	-10	43	23	32	14
9	60	32	10	- 2	11	- 9	34	32	36	17
10	51	37	..	- 1	22	- 3	27	15	38	20
11	50	30	14	..	28	7	32	16	45	21
12	53	33	19	- 2	22	20	40	26	62	29
13	40	34	23	8	20	7	37	30	47	34
14	32	30	25	9	22	9	11	2	41	21
15	29	26	27	10	35	11	20	3	33	24
16	23	21	28	23	29	15	28	7	35	27
17	25	15	33	17	26	22	28	16	58	30.
18	23	16	25	17	25	17	24	8	65	34
19	18	13	23	18	30	18	26	10	47	35
20	18	12	30	8	33	24	25	13	67	37
21	24	8	34	6	34	28	28	12	75	46
22	27	7	19	17	43	31	34	18	45	40
23	31	10	20	0	45	29	29	18	48	33
24	40	22	26	2	32	30	27	18	58	35
25	40	32	27	7	4	0	34	10	53	43
26	53	30	35	6	7	- 5	44	10	49	28
27	..	31	35	16	4	- 9	37	32	62	31
28	33	..	32	18	22	- 8	39	16	60	41
29	19	0	29	19	20	3			64	45
30	20	4	36	25	13	8			60	46
31			36	25	7	-14			34	28

Table 7--Daily maximum and minimum temperatures, degrees Fahrenheit, November 1, 1938, to April 30, 1939

Day	November		December		January		February		March		April	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	74	45	34	24	34	7	37	9	24	0	39	19
2	73	57	..	27	28	11	17	8	35	3	40	24
3	66	57	39	..	30	18	12	- 3	41	18	50	25
4	56	49	39	29	44	22	29	- 3	33	21	57	32
5	47	38	33	29	34	29	31	10	20	17	43	34
6	36	31	32	23	40	24	25	18	21	11	27	19
7	31	28	32	25	32	24	27	2	22	4	34	16
8	31	20	28	25	47	24	12	- 4	44	5	34	19
9	45	20	28	20	50	30	32	- 4	32	15	40	23
10	49	28	36	20	32	28	- 1	- 9	34	16	46	28
11	45	32	31	23	24	12	29	-16	..	22	25	24
12	58	34	20	14	28	12	38	-15	39	..	36	14
13	35	28	36	14	32	17	39	18	37	28	46	20
14	30	13	20	9	25	20	25	14	40	28	47	30
15	30	14	31	8	27	19	4	-12	15	6	54	32
16	45	14	36	17	19	5	11	-11	15	1	40	35
17	44	28	24	4	22	5	35	- 2	14	0	35	30
18	46	28	25	4	28	15	43	0	..	1	38	30
19	46	28	30	14	23	15	38	30	50	..	52	31
20	49	27	27	17	35	16	6	- 3	40	4	56	34
21	53	28	30	15	39	20	27	- 6	57	26	47	34
22	22	9	27	15	13	- 8	14	..	61	22	69	34
23	..	10	30	19	24	- 8	24	- 5	75	39	78	41
24	27	..	23	13	21	11	12	- 3	74	49	85	58
25	24	5	34	14	14	0	..	- 2	70	47	80	61
26	..	8	34	16	22	0	35	..	48	45	68	45
27	26	..	3	- 8	35	10	38	4	36	22	52	44
28	36	1	18	- 7	40	14	..	24	40	20	65	41
29	48	25	4	- 5	27	21			40	21	72	44
30	37	27	15	-12	27	11			47	20	75	49
31			17	-10	33	11			56	27		

Conclusions

(1) Frost-penetration is closely related to the height and density of the vegetal cover; that is, frost-depth is less under the heavier vegetal cover.

(2) The greater the depth of the snow-mantle the less the depth of frost-penetration, other things being equal.

(3) Atmospheric temperatures influence the depth to which frost will penetrate.

(4) If sufficient insulation is provided by snow or other material, frost may be drawn from the soil by warmth of Earth.

(5) The snow-mantle and frost disappear from the south exposures more rapidly than from the north exposures.

(6) An intense rain occurring when the surface three or four inches of the soil is thawed and in a saturated state would result in the erosion of a large portion of the unfrozen layer, especially in fall-plowed areas.

(7) Thawing takes place from the bottom of the frozen layer as well as from above.

References

[1] Lake States Forest Experiment Station, University Farm, St. Paul, Minnesota, Forest cover keeps frost line at shallow depth, September, 1937 (unpublished data).

Table 8--Frost- and snow-depth readings, January 1 to April 8, 1940, northeast exposure

Date	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches	Depth, inches, to		Snow-depth, inches
	Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line		Frozen soil[a]	Lower frost-line	
1940	Bare plot			Bare plot covered 12 inches snow			Six-inch snow-plot			Twelve-inch snow-plot			Twenty-four-inch snow-plot		
Jan 18	0.0	11.0	0.0	...	....	....	0.0	6.8	8.8	0.0	8.4	14.1	0.0	9.8	24.8
20	0.0	11.9	0.0	...	....	....	0.0	0.25	7.9	0.0	5.0	13.6	0.0	5.9	22.9
22	0.0	12.5	0.0	...	....	....	0.0	3.8	7.0	0.0	4.6	13.8	0.0	9.2	22.5
24	0.0	13.4	0.0	...	....	....	0.0	4.0	6.9	0.0	5.2	12.8	0.0	0.0	23.0
26	0.0	16.1	0.0	...	....	....	0.0	4.1	6.4	0.0	0.0	13.1	0.0	0.0	22.4
29	0.0	17.0	0.0	...	....	....	0.0	2.5	6.9	0.0	1.8	12.9	0.0	0.0	22.1
Feb 2	0.0	16.1	0.0	...	....	....	0.0	3.5	6.2	0.0	2.8	11.1	0.0	0.0	22.0
5	0.0	22.4	0.0	...	....	....	0.0	12.4	8.0	0.0	0.0	13.2	0.0	0.0	20.9
9	0.0	20.9	0.0	...	....	....	0.0	11.5	7.25	0.0	0.0	12.2	0.0	0.0	20.9
12	0.0	22.6	0.0	...	....	....	0.0	11.8	6.2	0.0	0.0	12.2	0.0	0.0	20.9
16	0.0	21.6	0.0	...	....	....	0.0	10.4	5.8	0.0	5.8	11.2	0.0	0.0	20.4
19	0.0	20.1	0.0	...	....	....	0.0	11.8	4.7	0.0	0.0	10.4	0.0	0.0	18.2
23	0.0	17.4	0.0	...	....	....	0.0	8.9	5.1	0.0	0.0	10.5	0.0	0.0	19.2
26	0.0	22.5	0.0	0.0	19.5	11.0	0.0	7.6	5.8	0.0	0.0	9.5	0.0	0.0	17.5
Mar 1	0.0	20.5	0.0	0.0	19.2	10.0	0.0	10.5	5.4	0.0	0.0	11.4	0.0	0.0	19.0
4	0.0	21.2	0.0	0.0	18.2	8.9	0.0	10.2	3.2	0.0	0.0	9.6	0.0	0.0	15.6
8	0.0	20.2	0.0	0.0	19.0	7.0	0.0	10.0	1.0	0.0	0.0	8.0	0.0	0.0	13.9
11	0.0	21.0	0.0	0.0	16.5	11.5	0.0	7.3	6.6	0.0	0.0	8.2	0.0	0.0	18.8
15	0.0	19.8	0.0	0.0	15.0	12.0	0.0	6.8	5.8	0.0	0.25	11.8	0.0	0.0	25.9
18	0.0	20.5	0.0	0.0	17.8	8.5	0.0	9.0	2.4	0.0	0.8	9.4	0.0	0.0	20.8
21	0.0	20.2	0.0	0.0	....	8.5	0.0	9.0	4.0	0.0	1.5	10.8	0.0	0.0	19.5
25	0.0	19.8	0.0	...	14.0	5.5	0.0	7.5	3.2	0.0	1.0	10.0	0.0	0.0	20.0
28	0.5	21.5	0.0	...	15.5	6.2	0.0	5.6	4.0	0.0	4.6	8.9	0.0	0.0	18.8
30	4.2	20.5	0.0	0.0	15.0	0.0	0.0	....	0.0	0.0	....	0.0	0.0	...	....
Apr 1	8.0	19.5	0.0	5.0	14.5	0.0	2.5	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	14.0	17.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	No frost		...	...	....	....	...	....	....	...	....	....	...	...	....

[a] Depth to unfrozen soil above frozen soil.

[2] William M. Briggs, Agronomist, Soil Conservation Service, Menomonie, Wisconsin, A brief study of the correlation of exposure, frost depth, manner and rates of thawing, runoff, snow depths, and vegetative cover in respect to soil conservation, Spring, 1936 (unpublished data).

[3] A. C. Arny, Associate Professor, Division of Agronomy and Plant Genetics, University of Minnesota, St. Paul, Minnesota, Alfalfa aids progress in Minnesota, Spec. Bull. 104, rewritten February, 1934.

Soil Conservation Service,
La Crosse, Wisconsin

DISCUSSION

KENNETH L. ROBERTS (Forest Service, Branch of Research, Flood-Control Surveys, Concord, New Hampshire), in personal conversation with the reader of this paper, said that observations during two winters on the Flood-Control Survey of the Merrimack River indicated that the soil froze early in the winter and remained frozen until the spring thaw under well-stocked coniferous cover with continuous canopy and in open areas observed in central New Hampshire, but that the soil in the well-stocked hardwood forests where observations were made, was practically free from frost for a considerable period prior to the time of the snow-melt in the spring. This may have been caused by the snow-cover, which was deeper and had a larger water-content in the hardwood forests than in either the coniferous forests or the open areas during the winter. Apparently some of the wet snow that fell on the coniferous trees and stuck to the branches evaporated before reaching the ground, and some of the snow in open areas was blown away or evaporated in the wind and sunshine. During the spring thaw, however, the coniferous forests in most cases retained the snow and the frost in the soil longer than the hardwood forests or open areas. The comparative effects of fully stocked coniferous and hardwood forests and open areas on snow-accumulation and soil-freezing were observed on a series of plots each set of which was located in such a way that they were at nearly the same elevation and similar in slope and exposure.

Further observations are being made which may help to establish more definitely all the effects of both fully stocked and partially stocked forest-cover on snow-accumulation, soil-freezing, and rate of snow-melt during gradual spring thaws and during spring floods. Relative to frost-cover in the forest-floor, a man who has worked in the forest for the last 50 winters stated that in 50 years 1939-40 was the first year he had ever seen frost in the woods which remained the whole winter. He was worried about heavy runoff and its relation to log-driving operations. The frost quite generally remains on the forest-floor, but on April 8, 1940, is showing signs of thawing following a recent heavy rain. Our survey indicates that there was no perceptible thawing due to the warmth of the Earth until a snow-cover of at least 25 inches existed and the specific gravity of the snow-cover had approached 0.25. Frost still remains and we feel that our sampler is giving satisfactory results.

EDWIN S. CULLINGS (Black River Regulating District, Watertown, N.Y.) suggests that even if frost forms in the soil before a sufficient cover of insulating snow is accumulated, the warmth of the Earth, if given sufficient time, will remove the frost before the spring thaw occurs. However, midwinter thaws may remove the snow and permit reentry of frost without sufficient time for its subsequent removal. The insulating power of the snow depends upon its own depth and the intensity of the cold. In the Eastern States during the past winter the cold was unusual in degree and continuity and the snow-cover continued to accumulate to maximum depth.

At Cranberry Lake in the Adirondacks, frost began to enter the soil October 18, when air-temperature of 0° F occurred. The record of soil-temperatures at Wanakena during the winter of 1939-40 is given in Table 1. Permission for the publication of Table 1 by the American Geophysical Union was given by the State Ranger School of the New York State College of Forestry at Syracuse University. A limited attempt at calibration, made a short time ago, indicates that the records need careful analysis for the elimination of errors, particularly those due to heat-losses, when the tubes were opened for observation. During the spring of 1941 the Ranger School intends to install thermocouples and after these instruments have been in operation a year or two, it will be possible to calibrate much more accurately than can be done at the present time. In Table 1 daily observations have been averaged over seven-day periods, beginning with Monday and ending with Sunday. The observations are made at depths of one, six, 12, and 24 inches. During the winter the snow will inevitably become more or less disturbed and packed around the thermometer, and therefore measurements near the surface of the ground are less representative of the true soil-temperature than those at greater depths. While at the one-inch depth the midwinter temperatures are 2° or 3° below freezing, our snow-surveys showed that in general there was little or no frost in the ground where the depth of the snow exceeded 24 inches. The measurements made at 24 inches should, however, be fairly representative of true soil-temperature, although even at this depth a certain amount of heated air is lost whenever the thermometer-tube is opened for observation.

Table 1--Soil-temperatures in degrees Fahrenheit, Wanakena, New York, weekly means, winter 1939-40
(Provisional results from New York Ranger School records subject to possible modification by control-measurements with thermocouples)

Week ending	Station No.							Air-temper. Sta.7	Station No.						
	1	2	3	4	5	6	7		1	2	3	4	5	6	7
	Depth, one inch								Depth, twelve inches						
1939,Oct 8	52.1	52.5	49.1	50.0	52.9	48.1	56.4	50.2	50.4	50.9	48.3	49.4	51.6	49.1	52.4
15	50.5	50.4	46.9	48.3	50.6	48.6	51.4	44.9	50.9	51.5	49.0	50.4	51.6	50.4	51.4
22	42.7	44.9	40.6	42.8	46.0	40.9	46.6	41.2	44.1	46.1	41.9	45.1	46.9	44.6	45.1
29	41.4	41.9	38.2	39.4	43.2	39.4	42.5	35.0	43.6	45.0	41.4	43.8	45.9	43.3	43.7
Nov 5	36.8	38.2	34.1	36.1	39.5	35.4	38.2	31.0	40.3	43.5	38.4	41.2	43.3	40.5	40.1
12	32.7	36.9	31.6	33.4	35.5	32.3	33.6	29.6	36.6	42.6	35.6	38.4	40.3	37.9	36.6
19	31.6	34.9	30.6	31.6	34.1	31.1	32.3	20.8	35.3	41.3	34.2	37.2	38.9	36.1	35.2
26	26.9	31.6	24.9	26.1	32.1	26.0	28.4	17.4	33.6	38.6	32.3	35.4	37.9	34.6	33.1
Dec 3	c30.0	c32.0	c29.8	c30.5	c32.5	c30.1	c30.8	31.0	c32.0	c37.1	c31.6	c34.1	c37.0	34.0	31.4
10	32.0	35.1	31.7	32.1	33.6	31.9	32.0	23.1	32.1	38.7	32.1	33.3	35.9	33.4	32.0
17	31.3	32.9	27.0	30.9	32.0	29.1	31.6	14.2	32.4	37.4	31.9	33.6	35.7	32.9	32.4
24	32.0	34.7	30.1	32.0	32.9	31.6	32.0	21.1	32.7	37.9	31.6	33.4	35.4	32.9	32.6
31	31.6	34.3	26.0	30.3	32.4	27.1	31.3	5.0	32.4	36.3	31.0	32.9	35.9	32.7	32.4
1940,Jan 7	31.0	33.0	26.3	29.0	31.1	28.1	30.0	0.3	31.9	35.1	30.0	32.1	33.9	31.7	31.9
14	28.7	32.6	25.7	28.9	30.9	25.9	30.3	13.4	32.0	35.1	30.0	32.6	34.6	31.0	31.7
21	29.4	32.0	28.4	29.7	30.4	28.6	29.7	3.9	31.1	33.7	30.4	32.0	33.4	30.6	31.4
28	29.4	30.3	27.0	29.4	29.6	27.6	29.6	0.5	30.9	33.4	29.7	31.3	33.1	29.9	30.9
Feb 4	29.0	29.7	26.4	28.9	29.4	26.1	29.1	1.5	30.0	33.4	29.0	31.4	32.7	29.1	30.0
11	29.3	30.0	29.0	30.0	30.0	28.9	29.9	21.0	31.0	33.6	30.7	31.9	33.4	30.9	30.9
18	29.9	30.0	29.0	29.0	30.0	28.9	29.7	13.4	32.0	33.7	30.6	31.6	33.0	30.9	31.4
25	29.3	30.7	28.9	29.4	30.3	28.9	29.4	15.5	31.9	34.4	30.6	31.7	33.4	30.9	31.4
Mar 3	29.0	30.6	27.7	29.6	29.7	28.3	29.6	9.3	31.1	33.6	29.9	31.1	33.1	30.3	31.1
10	30.0	31.0	29.1	30.0	30.0	30.0	30.0	22.2	32.0	35.0	31.0	32.0	33.7	32.0	32.0
17	30.0	31.0	28.6	29.0	30.0	28.7	30.0	14.9	31.0	34.6	30.0	31.0	32.6	31.0	31.1
24	30.0	31.0	29.0	29.0	30.0	29.0	30.0	13.2	31.0	35.0	30.0	31.0	33.0	31.0	31.1
31	30.0	31.7	29.0	29.4	30.0	29.0	30.0	26.6	31.7	34.9	30.7	31.6	33.7	31.6	31.7
	Depth, six inches								Depth, twenty-four inches						
1939,Oct 8	50.8	51.4	48.4	49.0	51.4	47.7	54.1	50.2	51.2	51.0	48.3	49.4	51.6	50.3	52.6
15	50.7	51.6	48.0	49.5	51.1	49.2	51.5	44.9	51.6	51.0	49.2	50.1	51.6	49.8	51.8
22	43.3	45.2	40.7	43.2	45.3	41.6	45.8	41.2	46.6	48.1	44.4	46.7	48.5	48.1	47.6
29	42.5	43.7	39.7	41.1	44.2	40.4	42.8	35.0	45.6	46.7	43.6	45.4	47.2	46.1	46.4
Nov 5	38.6	40.4	35.3	37.6	40.3	36.2	38.6	31.0	43.4	45.3	41.5	43.9	45.7	44.8	44.0
12	34.7	39.8	33.1	34.9	37.1	33.7	34.8	29.6	40.2	44.1	38.4	41.4	43.0	42.4	40.4
19	33.4	37.7	32.0	33.6	35.4	32.3	33.3	20.8	38.5	43.4	36.6	39.6	41.0	40.9	38.8
26	29.6	34.8	26.2	29.0	34.1	28.1	29.5	17.4	37.2	41.5	35.4	38.2	39.9	39.1	37.4
Dec 3	c30.3	c34.1	c30.2	c30.9	c33.5	c30.7	c30.2	31.0	c36.0	c40.1	c34.2	c37.0	c39.0	38.9	36.0
10	32.0	37.1	32.0	32.0	34.0	32.0	32.0	23.1	34.4	40.0	34.3	36.0	37.9	37.6	35.1
17	32.0	35.4	28.9	31.4	33.9	30.6	32.0	14.2	34.4	39.4	34.0	35.6	37.4	36.4	35.3
24	32.0	36.3	31.1	32.0	33.9	32.0	32.0	21.1	34.6	39.6	33.4	35.9	37.4	36.4	35.4
31	31.6	35.3	27.3	30.3	33.3	29.3	31.7	5.0	34.1	38.0	32.9	34.7	36.1	35.3	34.4
1940,Jan 7	30.7	34.0	26.7	30.0	31.9	29.1	31.0	0.3	33.7	37.0	31.7	34.3	35.6	34.4	34.0
14	29.6	33.7	26.7	29.6	32.0	28.4	31.3	13.4	33.7	36.9	32.4	34.4	36.4	34.9	34.7
21	30.1	32.6	29.4	30.1	31.3	29.6	30.7	3.9	33.3	36.1	32.0	34.3	35.1	33.7	34.0
28	30.0	30.9	28.4	30.0	30.6	28.1	30.3	0.5	33.0	35.1	31.1	33.3	34.4	32.6	33.3
Feb 4	29.3	30.6	27.4	29.4	30.4	27.7	29.7	1.5	a32.0	a34.7	31.0	32.9	35.0	32.7	33.0
11	30.0	31.0	29.0	30.0	31.7	29.0	30.0	21.0	b33.0	35.6	31.6	33.0	35.0	33.3	34.0
18	30.0	30.4	29.1	29.6	30.3	29.4	30.1	13.4	33.0	36.0	31.6	32.9	34.2	32.9	33.4
25	29.9	31.9	29.0	30.0	31.9	29.4	30.3	15.5	32.9	35.9	31.4	32.9	35.1	33.0	33.7
Mar 3	29.7	31.6	28.4	30.1	31.1	28.7	29.7	9.3	32.3	35.1	31.1	32.3	34.3	32.7	33.0
10	30.0	32.0	30.0	30.0	31.0	30.0	31.0	22.2	33.0	36.0	31.6	33.1	35.0	33.4	33.7
17	30.0	32.0	29.0	30.0	31.0	29.0	30.0	14.9	32.0	35.6	30.7	32.0	34.6	32.7	32.0
24	30.0	32.1	29.3	30.4	31.4	29.0	30.0	13.2	32.1	36.0	31.1	32.1	34.7	33.0	32.0
31	30.7	32.7	29.4	30.7	31.9	29.9	30.7	26.6	33.1	36.0	31.6	32.7	35.3	33.0	32.7

Notes: Letters a, b, and c preceding value indicate number of daily readings missing from weekly averages, namely, a = 1, b = 2, c = 3 days. Weekly period is from Monday morning to Sunday night and date given is last day of period. Station 1 is open brushy depression known as the "frost-pocket." Station 2 is on steep hillside with southeasterly exposure in small opening in woods. Station 3 is in red-pine plantation on gentle slope with southern exposure. Station 4 is in mature virgin timber of hard and soft wood. Station 5 is in second-growth hard wood on gentle slope with southern exposure. Station 6 is in spruce-swamp. Station 7 is the central control-station on nearly level land surrounded by spruce- and pine-plantation.

ASHTON R. CODD (Hydrologic Supervisor of the U. S. Weather Bureau, Portland, Oregon), in connection with erecting seasonal precipitation-gages, has had opportunity to observe the occurrence of frost on the higher slopes of the Rocky Mountains.

At most of the locations in the autumn, deep frost was encountered and his following report of April 19, 1940, therefore, indicates whether the frost was still found in the spring:

Relative to frost in the ground as discussed in previous letters and mentioned at Stanford during the January Conference, there are attached copies of letters received from two of the observers.

Fred D. McLaren's letter of March 10, 1940, from Grand Lake, Colorado, is very good and contains the type of data desired. There has been no report from him since that date.

H. H. Burt's report from Silverton, Colorado, gives somewhat the same picture. However, the Silverton location is not indicative of watershed-conditions because the gages are located on a grassy pasture which is alluvial material in the bottom-lands of a river-cut canyon, perhaps never flooded, and conditions are not representative of the higher mountain-slopes.

Out of six letters written, these are the only two that have answered in any detail. However, in our reports of March 31, 1940, there were several notations, namely: Frost still under snow at Silverton, Colorado; there was frost 12 inches deep (east of Steamboat Springs) at Rabbit Ears Pass, Colorado; frost was going out of ground under snow at Grand Lake, Colorado. This report would indicate that as the snow goes out so does the frost, and apparently the frost goes first.

When taking some snow-samples at Brighton, Utah (8,700 feet), on April 15, 1940, it was noticed that in all the samples the botton two inches of core were well saturated with water and the ground under the snow was unfrozen and water-soaked (43 per cent density). From this I judge that the snow is about ready to move out. There were eight inches of frost here in November.

Fred D. McLaren's report from Grand Lake, Colorado, March 10, 1940--In answer to the request of February 26, 1940, I have made some tests to determine the amount of frost that is in the ground at the present time with the following results: In open ground, where there was some moisture, about 12 inches of frost under 16 inches of snow were found; in lodgepole-pine forest no frost at all under 14 inches of snow was found in some places. It appears to me that the high ground was so dry that there was no moisture to freeze.

H. H. Burt's frost-report from Silverton, Colorado, March 31, 1940--Using a quarter-inch steel rod as a probe, a number of tests were made in the vicinity of gage-towers Nos. 2 and 3 with the following results: Ice was found to be underneath all remaining snow. At bare ground where water was standing and from which the snow had melted within the past few days, frost was found below the surface at depths of from one inch to ten inches. No digging was done to determine actual frost-thickness. At one stop, from where the snow probably melted early in the week--also on slightly higher ground than the rest--the rod was shoved to a depth of 20 inches without locating any frost. One inch of water was standing around tower No. 3 at time of test (8:30 a.m.); frost-depth (thickness) March 1, 1940, was 11 inches (had to blast for this).

THE RELATION OF SNOW TO MAXIMUM FLOOD-PEAKS

Walter J. Parsons, Jr.

In the design of control-works on rivers, the provision of adequate protection against unusual flood-flows is essential. Historical flood-records usually give sufficient information to permit the design of the ordinary operating parts of the structure. The design of the safety-valve that will preserve the structure from disastrous failure with attendant loss of life and extraordinary loss of property requires a close estimate of the worst possible flood. This flood is not a usual or reasonably expected flood but one which is the result of the worst possible combination of factors. The touchstone is not what usually occurs, but what might reasonably occur. For rivers draining areas free from the accumulation of appreciable quantities of snow, this estimate will normally start with a determination of the worst possible storm-precipitation. For areas where snow does accumulate, the problem becomes more complicated. The starting point then becomes not the precipitation that fell but rather the "effective precipitation" after modification by the accumulated, temporarily-frozen precipitation on the ground and its associated phenomena. The writer will restrict himself to the problems encountered on rivers draining the high mountain-area along the Pacific Coast where the snow-cover over a portion of the drainage-area may reach depths in excess of four feet and the worst possible storm may occur during the winter season when there is a heavy snow-cover. The streams draining the western slopes of the Sierra Nevada in California provide a good illustration of this type of stream.

The snow-cover on the mountain-slope can best be pictured as a wedge with its feather-edge at about the 5,000-foot level. Above this level, the snow-depth increases rapidly up to depths of as much as 30 feet. The snow is deposited at temperatures close to the freezing point and is rarely subjected to prolonged cold spells that would chill the mass of the snow radically below freezing. However, temperatures are low enough to freeze the surface-layers of the ground or to seal them with a sheet of ice. Although this impervious condition of the ground is sometimes removed through thawing of the ice by the residual heat of the Earth, this cannot be counted on at the time of occurrence of the storm and a relatively impervious surface beneath the snow-cover must be assumed. The snow-cover is soon compacted by settling and partial melting, and apparent densities are known to reach, and even exceed, 50 per cent.

General prolonged storms occurring during the winter season, which cause intense rainfall from the valley-floor upward to the 9,000- or 10,000-foot level, produce the highest known floods in this region. The storm may last for as long as 15 days but the intense rainfall is intermittent with a maximum duration for any one period of about 18 hours. Between these intense periods of rainfall the sky remains overcast. The snow is melted primarily by the heat of the warm, moist air-mass moving up the slope of the mountains at velocities as high as 40 miles per hour, rather than the heat of the falling rain. During the storm-period, air-temperatures often reach 60° F at the snow-line, with diurnal fluctuations sometimes less than 5°. As a result, the rate of contribution of snow-melt to runoff is much more uniform than the contribution directly from rainfall.

Analyzing the contribution to runoff, from each zone of elevation within the drainage-area, the following summary can be made. In Zone 1 (below the snow-line) runoff is solely the result of the rain, and runoff-factors range upward to 65 per cent. (The per cent in each case is the ratio of the runoff to the actual rainfall.) In Zone 2 (from the snow-line upward to an elevation where the snow is about two feet deep) runoff is the combined result of rainfall and snow-melt, both of which pass through or over the snow-cover, being partly absorbed in the pores of the snow. The "effective" rainfall may be larger than the actual rainfall and behaves similarly to rain alone. The runoff-factor based on "effective" rainfall may thus be more than 100 per cent. In Zone 3 (from an elevation having snow-depths of about two feet to an elevation having depths of about four feet) the rain and snow-melt must largely pass through the porous snow-cover and the "effective" rainfall is generally less than the actual rain, large quantities being stored in the pores of the snow. The runoff is much more prolonged and follows a different pattern than the runoff from Zones 1 and 2. The runoff-factor based on rainfall may be as high as 80 per cent. In Zone 4 (above an elevation where the snow is about four feet deep) rainfall and snow-melt make no contribution to flood-runoff, all rain and snow-melt being absorbed by the snow. These zones move slowly upward during a prolonged storm-period and must be refigured at frequent intervals.

Since precipitation, rainfall, snow-cover, and snow-melt are all closely linked with elevation, it has been found very convenient to assemble data concerning these on a diagram having elevation as the horizontal coordinate. The elevation-precipitation curve for the first day of the worst possible storm is first plotted. This is modified into an elevation-rainfall curve by cutting off the upper end of the elevation-precipitation curve at the highest possible elevation that winter storm-precipitation can occur as rain. A series of elevation-snow-cover curves are then drawn corresponding to several different elevations of snow-line and the snow-wedge above it, covering the possible range. Elevation-effective-precipitation curves are then drawn for the combination of the precipitation of the first day and the snow-melt corresponding to each alternate location of the snow-line. A similar set of curves is drawn for each succeeding day of the storm-period, showing the progressive retreat of the snow-wedge.

Using these data, a synthetic hydrograph is developed for each original elevation of the snow-line. From this series, the worst possible flood-hydrograph is selected. Since the storms with which we are dealing have periods of intense precipitation considerably shorter than the concentration-period of the river-basin, the worst possible flood-peak will usually result when the original elevation of the snow-line is such that the snow-line will be retreating across the zone of maximum effective width of drainage-basin at the time of occurrence of the maximum intensity of the storm. However, the optimum location of the snow-wedge must be determined by trial, since the flood-producing characteristics of each river are unique. The flood on one stream may be increased by the presence of a snow-cover, while on its neighbor, the flood may be decreased.

The writer believes that this general method of analysis leads to reasonable estimates of the worst possible flood from mountain-streams and recommends it to the attention of his fellow engineers.

U. S. Engineer Office,
Sacramento, California

THE RELATION OF SNOW TO MAXIMUM FLOOD-PEAKS: A DISCUSSION

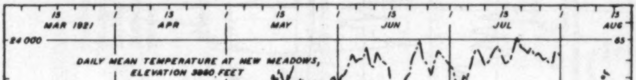
J. E. Church

The following investigation was suggested in a personal conversation with Walter J. Parsons, Jr., of the United States Engineer Office, Sacramento, California, but was carried out in cooperation with Major R. H. Elliott, District Engineer, Allen L. Darr, and John B. Woffenden of the Hydrographic Staff, Corps of Engineers, Bonneville, Oregon.

The arrangement of topics follows mainly the formal questionnaire submitted with discussion of data associated with the Payette River, Idaho, and streams in the Great Basin. The abnormally high temperature that prevailed throughout the past winter of 1939-40 afforded unusual data on the upward creep of melting in snow of various depths and increasing altitude. A very special case of snow-flood without rain was discovered on the Humboldt River, Nevada, in the identical period (March, 1910) of the flood of its distant neighbor, the Palouse River, Washington, proposed as one of the Engineers' projects for study.

Letters from Major Elliott of March 22 and June 6 will best introduce the paper:

"In connection with flood-control projects here in Oregon, Idaho, and Wyoming, we desire to arrive at an estimate of the greatest possible flood likely to occur. For rivers whose sources are high in the mountains at altitudes of 7,000, 8,000, 9,000, and 10,000 feet, the snow stored in these upper regions contributes from 50 per cent to possibly 75 per cent of the flood-water when melted. However, it seems that if an exceptionally cool spring running through May with a larger than average snow-cover in the hills were to be followed by an excessively warm June with heavy, unseasonal rains, the maximum flood would be produced.



Between elevations, feet	Percentage of area
3,000- 4,000	6.0
4,000- 5,000	20.5
5,000- 6,000	26.9
6,000- 7,000	23.5
7,000- 8,000	17.9
8,000- 9,000	3.3
9,000-10,000	0.7

Fig. 1--Hydrographic and meteorological data for area above Horseshoe Bend gaging-station, Payette River, Idaho, March to August, 1921

Snow--solid and full of water--end of March: Salmon-Payette Divide, 144 inches; Big Creek Summit, 108 inches.

"Is it your thought that the sequence of events outlined above would produce the maximum flood? Do you find that the snow-cover is much heavier on the leeward side of the mountains, that is, away from the direction of the prevailing winds? The greatest depth of snow is of course below the snow-cornices on the leeward side of the summits but perhaps you have knowledge as to the distribution on both sides of the hills. Are you aware whether any one has made a study of the relation between temperature and the rate at which snow melts? Also of the effect of warm rain in melting snow, that is, rate at which the snow melts?

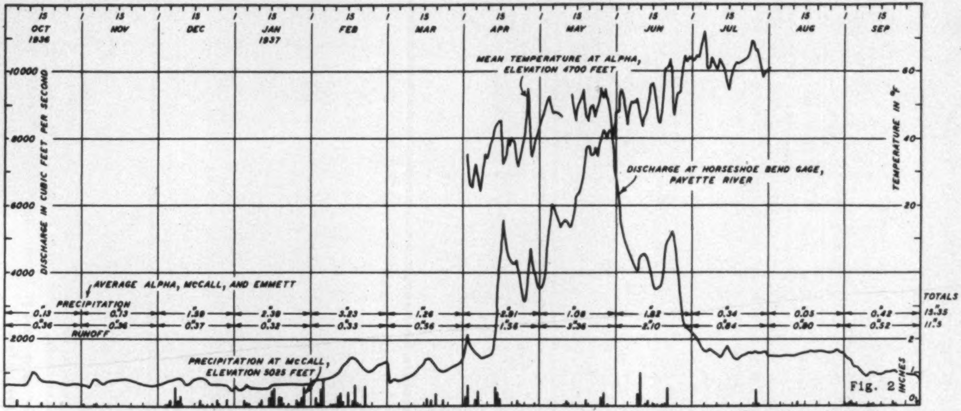


Fig. 2

Snow-courses	Elevation feet	Av. snow-depth at end March inch	Departure from normal	Average water-content	Snow-courses	Elevation feet	Av. snow-depth at end March inch	Departure from normal	Average water-content
Alpha	4700	18	+6	....	Secesh Summit	6475	73	..	28.9
Big Creek Summit	6608	76	..	23.9	Squaw Meadows	5800	70	..	29.2
Cascade	4750	T	..	....	Tripod Mountain	4300	..	..	....
Deadwood Dam	5500	34	+2	16.4	Garden Valley	3300	0	-4	....
Deadwood Summit	7000	74	..	27.4	Kirkham	3900	T	-5	....

Note: Snow quite solid; ground under snow generally dry; total precipitation October 1, 1936, to March 31, 1937, 65 per cent of normal.

"The enclosed graph (Fig. 1) shows the relationship between temperature and runoff on the upper portion of the Payette River Drainage-Basin in southwestern Idaho. It covers the greatest flood in some 30 years of record. If an assumption be made that the runoff shown on this graph were to occur in 30 days the peak-discharge might have reached from 45,000 to 50,000 second-feet.

"Any information you can give us of floods resulting from the rapid melting of snow as a result of high temperatures, with or without rain, will be greatly appreciated. . . . ."

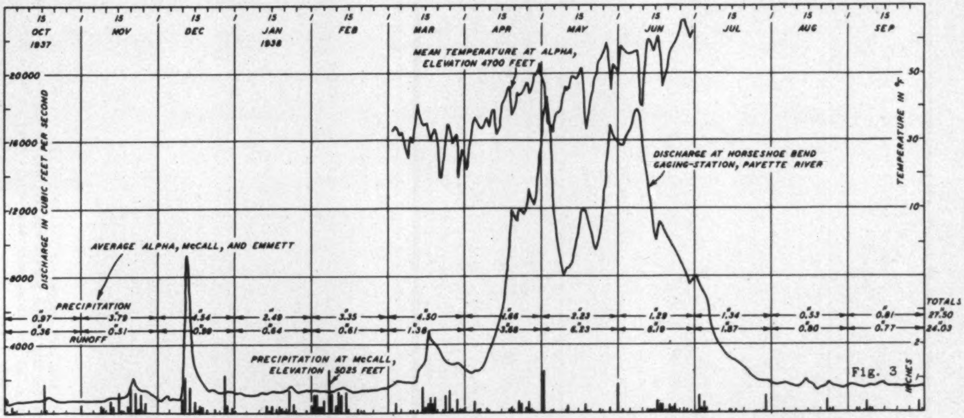


Fig. 3

Snow-courses	Elevation feet	Av. snow-depth at end March inch	Departure from normal	Average water-content	Snow-courses	Elevation feet	Av. snow-depth at end March inch	Departure from normal	Average water-content
Alpha	4700	32	+17	....	Secesh Summit	6475	144	+66	51.0
Big Creek Summit	6608	110	...	37.5	Squaw Meadows	5800	134	...	49.5
Cascade	4750	20	+ 1	....	Tripod Mountain	4300	0	...	....
Deadwood Dam	5500	67	+29	23.3	Garden Valley	3300	0	- 4	....
Deadwood Summit	7000	150	+51	59.8	Kirkham	3900	8	+ 3	....

Note: Snow-cover well packed; ground under snow unfrozen and well saturated; precipitation from October 1, 1937, to March 31, 1938, was 120 per cent normal.

"In your letter of April 12, 1940, you expressed a desire to be able to compare the snow-measurements given on the hydrograph of 1921 for the Payette River above Horseshoe Bend with snow-surveys of more recent years taken on the same spot. Enclosed are three hydrographs (Figs. 1-3) of the Payette above Horseshoe Bend giving the information which will permit the desired comparison.

"One other statement covering the cause of the greatest flood on the South Fork of the Palouse River in southeastern Washington should be of interest. The flood occurred on March 1, 1910, and was the result of a one-day rain falling on 12 inches to 18 inches of loose snow and the rapid melting of the near slush that resulted by a chinook-wind on the following day. This sequence of events, I believe, agrees with your ideas as to the cause of large floods from melting snow.

"After you have had time to look over the enclosed hydrographs, I would appreciate your conclusions in regard to reasons for the height and sustained flow of the flood of 1921 on the Payette. This flood was the greatest in 30 years of record."

My resulting argument follows: At the Stanford Meeting of the Western Interstate Snow-Survey Conference and Section of Hydrology of the American Geophysical Union, Mr. Parsons discussed the possible causes of the greatest flood that could be expected and the means of forecasting it. At that time it was suggested that the snow-cover at high elevations was practically impregnable and that the source of floods should be sought in the excess of snow in the proximity of the normal snow-line. He was urged to present a paper on his further investigations at Seattle in June 1940 (see preceding paper).

The source of maximum floods--Regarding the location of the source of the maximum flood, I should be inclined, as said to Mr. Parsons and since that time to others, to place it near the snow-line rather than in the upper reaches of the watershed for the reason that the area of the watershed is greater at the snow-line than toward the crest, the temperatures are higher and therefore more effective, and the body of the snow is less deep and therefore less capable of catching the heavy rains and holding them in suspension. Furthermore, even if the month of May should be cold, the temperature of the incoming season will be gradually rising, so that at worst the snow at the lower elevations will begin to melt or at least to settle under the influence of the temperature. As a rule it is rare for the temperature-departure of a spring month to be more than 10° F. The normal increase in temperature from month to month in the spring is 7°. Therefore, a minus departure of 10° would, in effect, be only 3° colder than the previous month if it had been normal. An example of the march of the season is the increase in normal temperature at Truckee (elevation 6,200 feet) as follows: March, 33°.4; April, 40°.6; May, 48°.1; June, 56°.7; July, 63°.5. Consequently the snow at the lower elevations would begin to shrink in area and one of the potent sources of spring floods would gradually vanish. Therefore, when the excessively warm June arrives, even with unseasonal rains, the higher snow would be left alone as a flood-producing menace without maximum assistance from the lower snow. Furthermore, the higher snow-cover because of its natural protection from melting by temperature or rain will produce relatively less flood. Of course, conditions might arise in which the higher snow of itself could produce a greater flood than the lower snow, merely because the temperature of June is normally higher than that of May. However, I believe that destructive floods must be expected earlier in the season, at least that the probability date should be set early rather than late.

The graph of the Payette River appears to indicate high seasonal runoff rather than flood-crest. The notation on the graph (see Fig. 1) kindly forwarded by Mr. Sherman refers to a snow-cover at the close of March of 108-144 inches, "solid and full of water." This would mean probably from 40 to 50 per cent water or a maximum of 72 inches water-content. These measurements, however, appear to have been taken near the summit, where snow was deepest. With a series of graphs the underlying causes of the high water of 1921 could be determined. The precipitations in May and June (7.55 inches and 7.41 inches) appear high, but during the entire period the most intense precipitation did not equal quite one inch daily. The rise in the runoff was evidently responsive to the rise in temperature, yet the mean rise in temperature from May through June did not greatly exceed 10°, that is, 10° for each of the two months. The maximum appears to have been less than 25°. On June 10 the peak of the River fell rapidly and after maintaining its level for five days fell gradually from June 25 to July 15 to what is probably its usual late summer discharge since the temperature continued rising after the runoff-peak was attained, and the decline was plainly due to the exhaustion of the snow-field. There is doubtless here an example of the effect of temperature-rise on rise in stream-runoff. The total amount of flood-water seems dependent upon the snow-cover.

The graphs of the Payette for 1937 and 1938 appear to verify the above assumption. In these, snow-survey measurements are available for Big Creek Summit where 108-inch snow-depth was noted at the end of March, 1921. In 1937 (Fig. 2) the snow-depth was 76.0 inches (water-content 23.9 inches). Both peak and total discharge were low.

In 1938 (Fig. 3) the snow-depth was 110 inches (water-content 37.5 inches). The peaks were correspondingly large. The first was a spire caused plainly by rising temperature abetted by a heavy rain. The second was a recovery based on snow-cover mainly and the season's normal rise in temperature.

The snow-depth in 1921 (possibly a single measurement rather than the average of a snow-course) was 108 inches or two inches lower than the measurement in 1938. However, the density of the snow-cover in 1937 and 1938 was only 31.4 and 34.1 per cent whereas the notation on the snow-cover in 1921 was "solid and full of water." Even at the conservative density of 40 to 45 per cent (found frequently in the Chelan Basin [p. 890]) the water-content of the snow would be 43.2 to 48.6 inches as compared with 37.5 inches in 1938, or a gain of 15 to 25 per cent. If the snow had been 50 per cent dense, its excess over the snow-cover of 1938 would have been fully 40 per cent.

Unfortunately the temperature-graph in 1921 is for elevation 3,860 feet while the graphs for 1937 and 1938 are for elevation 4,700 feet. No relative divergence in temperature, however, is noticeable.

Only one case of flood due to rise in temperature has been quoted to me. There are probably others but apparently not sufficiently powerful to draw attention to them. This instance was in the Black River Basin, New York State, where a flood from snow only, that is, without assisting rain, occurred in June because of excessive rise in June temperature to 70° F. I am not certain whether the 70° quoted by E. S. Cullings, Secretary, Black River Regulating District, Watertown, New York, represents mean temperature or maximum. He stated that such floods are rare. Mr. Cullings is an authority on the effect of precipitation on runoff and was long in charge of the New York Cooperative Snow-Surveys. (However, an unusual but inevitable case of snow-flood caused by temperature alone has since been discovered in our own Humboldt Basin, Nevada [pp. 966-967].)

Snow-shadow--Your question regarding the relative heaviness of the snow-cover on the windward and leeward side of the mountains is evidently based upon the effect of winds in carrying moisture from the windward to the leeward side of the slope. There is doubtless a rain- or precipitation-shadow on the leeward side but its effect is so minor that it is difficult to measure its quantity. The drifting of snow from windward to leeward of mountains, if the mountains are greatly exposed to the wind, is obvious and may have some effect in loading lee basins with the snow taken from others to windward. This theory of transport has been proposed to account for the building up of glaciers in adjoining basins while the glaciers in neighboring basins were diminishing. On Mount Rose the movement of snow from the windward side to the leeward can be seen in action. This makes for the conservation of snow since the leeward side of the mountain is also its shaded side. However, this effect is not carried to an extreme distance beyond the crest. Cornices are very obvious but limited in area. The presence of timber-line forests quickly brings drifting snow to rest. In Ward Basin, west of Tahoe, no noticeable difference quantitatively was found in the depth of the snow below the crest on the leeward side and at Page Meadows a mile or more distant. Furthermore, we feel certain that neither spot was the recipient of much drift-snow from the windward side of the range. This movement therefore is regulated largely by the presence of forests.

The "rain-shadow" is a most interesting phenomenon theoretically. Mr. Kraebel of the San Dimas Experimental Forest at Los Angeles, believes that he has found some evidence of heavier precipitation on the lee slope of one of his watersheds than on the opposite windward slope. He commented on this fact in a report on the San Dimas Forest presented at the Regional Meeting of the Section of Hydrology of the American Geophysical Union at Stanford University, January 12-13, 1940 [Trans. Amer. Geophys. Union, 1940, pp. 84-92]. He theorized that the moisture-laden air-currents were carried over the crest before depositing their burden. On Mount Rose we have found the air-currents sweep over the crest and return up slope from the opposite side with such strength that in descending the mountain we were actually forced to throw our weight upon the wind in order to make progress downward. There is here an opportunity for condensation of vapor probably in excess of the condensation caused by the impact on the windward side and therefore possibly this movement may create an excess in precipitation on the lee slope. This movement of the air can be seen easily in the winter time in the great banners that play from mountain-peaks at the height of gales. This phenomenon is, of course, entirely distinct from the increase of precipitation with altitude on the windward slopes of mountain-ranges, which is followed on the leeward side of such ranges with decrease in precipitation from the crest to the base. However, on the windward slope of the Sierra the altitude of maximum precipitation may lie below the crest.

An example of such precipitation is 58.88 inches at Blue Canyon, California, and only 7.63 inches at Reno, Nevada. Similarly as between parallel mountain-ranges, the range to the lee on the Pacific Coast has less than the one to its windward. For example, the normal snow-cover at Donner Summit (elevation 7,000 feet) at the crest of the main Sierra is approximately 40 inches while at Marlette Lake (elevation 8,000 feet) at the crest of the Carson Range, east of Lake Tahoe, it is approximately 20 inches.

Rate of melting--Some study has been made of the relation between temperature and the rate at which snow melts. Since runoff from such snow is dependent upon the original density and the depth of the snow, the problem is complex. Dean George D. Clyde, School of Engineering, Utah State Agricultural College, Logan, Utah, has published some results on his studies in "Snow-melting characteristics" [Bull. 231, Utah Agric. Exp. Sta., August, 1931]. While this subject is almost untouched, considerable work has been done regarding the ability of snow to hold water in suspension. Three papers on this latter subject were prepared for the meeting of the International Commission of Snow at Washington in September 4-15, 1939, and were printed in the form of proofs. These are: "Wasserdurchsickerung und Wasserrückhaltvermögen der Schneedecke" by Dr. Max Oechslin; "Die Fähigkeit des Schnees, Wasser Durchzulassen und Aufzuspeichern" by Dr. Hans W:son Ahlmann; "The bearing of snow permeability and retentivity on the density increase of firn and ice band formation in glaciers" by T. P. Hughes and Gerald Seligman. A paper by Dr. Robert E. Horton on "Phenomena of the contact-zone between the ground-surface and a layer of melting snow" has appeared [Bull. No. 23, Internat. Assoc. Sci. Hydrol., 1938] and the volume by Swiss scientists on "Der Schnee und seine Metamorphose" is being translated by the United States Forest Service and United States Weather Bureau [a summary appears in Trans. Amer. Geophys. Union, 1940, pp. 393-395].

Effect of rainfall on snow--Another phase of melting snow is the effect of rainfall upon snow-cover. The most recent paper on this subject is probably one by O. N. Rugen, presented at the San Francisco Meeting of the American Society of Civil Engineers, mid-summer 1939. Mr. Rugen is a member of the Army Engineers Office at Los Angeles. His paper will be presented again at the Seattle Meeting of the Section of Hydrology, American Geophysical Union, having been highly appreciated by the Civil Engineers and therefore requested for presentation in the Pacific Northwest [see pp. 1033-1044].

The paper by Bertram S. Barnes on "Problems of stream-flow forecasting on the tributaries of the upper Mississippi" [Bull. Amer. Met. Soc., pp. 96-100, March 1940] quoted by LeRoy K. Sherman in a letter to you, provides some data of special value. He states: "Contrary to popular belief, even a warm rain is not capable of melting very much snow. The amount may readily be calculated from the temperature of the rain and the heat of fusion of snow. If the temperature of the rain were 50° F it could give up 18 Btu/lb before it became chilled to the freezing point. If the temperature of the snow is 32°, 143 Btu/lb of snow will be required for thawing. Rain at 50° would therefore melt one-eighth of its weight of snow; at 40° it would melt only one-eighteenth of its weight; at 60° it would melt one-fifth of its weight of snow; and at 70° it would melt one-quarter of its weight. The striking-energy of rain falling at a velocity of 50 ft/sec can generate only one-twentieth of one Btu/lb and may be neglected. The effect of warm air accompanying the rain is usually much greater than that of the rain, especially if turbulence is present at the ground-level."

It will be noted that the rain of 40° F, which is the ordinary rain of spring when the precipitation oscillates from rain to snow, will melt only one-eighteenth of its weight. Therefore, little damage to the snow-cover results. Even at 60° the rain would melt only one-fifth of its weight of snow. Consequently, if the snow-cover is heavy, the rain must be very heavy indeed to remove it entirely. Rather it would pass through the snow with little accretion of moisture and thus have an effect only slightly greater than that of rain unaided by the snow. If the snow has not attained its full density, some of the rain will be held in suspension by the snow, thereby increasing the density of the latter to its point of ripeness.

Snow-density--The term "ripeness" represents the density at which snow can no longer hold water in suspension. Snow laid at an initially light density attains its ripeness at approximately 35 per cent, but snow that is wind-blown soon attains an initial density of 40 per cent and becomes ripe at approximately 50 per cent. There are thus two general types of snow, the usual type at lower elevations and protected from major wind-movement and the high-altitude snow that is subjected to wind. The former type of snow will sustain relatively more rain-water than will the latter. On the other hand, the latter has greater depth and is situated at the altitude of cold rains rather than warm ones. It is difficult, therefore, to determine the relative efficiency of the two types of snow. It has been suggested, particularly by Carroll F. Merriam, that there may be a critical density and a critical temperature at which snow suddenly loses its power of capillarity and allows rainfall to pass directly through and even breaks down into slush and water. The Susquehanna Basin is doubtless the best field in which to study this possibility.

It is true that old snow or firn is extremely granular and possesses large voids. Therefore, it has very slight power of resisting percolation but breaks down slowly by the passage of water through it. Snow of lighter density, which has not had the opportunity to resist the breaking down of its crystals by warmth or rain, may more readily form slush, particularly if a crust of ice has formed beneath it, thus preventing the water from draining rapidly away. Stages like both of these are the last phases in melting and probably have little part in causing the heavier floods. Of the two the latter is probably the more effective as a sudden producer of melt-water.

The above questions, which I had not earlier worked out in detail, appear to confirm my opinion stated to Mr. Parsons that the maximum flood was to be expected near the usual snow-line where the snow would not be sufficiently deep to resist melting by the rain and would thereby add its increment to the rainfall. This snow-line I called the feather-edge of the snow. In case this feather-edge extends far down the valley and even possibly covered the valley-floor, where temperatures are normally high, a potential flood-hazard exists and needs only an intense rain to unleash it. On the other hand, if the snow-line is high, the flood-hazard will depend on the intensity of the rain alone.

Cause of flood in the Sacramento Basin, 1937--The severe flood in California of December, 1937, was caused by heavy rainfall from December 9 to 12 falling mainly upon bare slopes or upon snow at higher elevations that was still so thin as to be readily melted. This flood has been discussed in detail by E. H. Fletcher, Meteorologist, United States Weather Bureau, Sacramento, California, under the title "Floods in the Sacramento Valley, California, December 1937" [Mon. Weath. Rev., December 1937, pp. 441-445]. I agree with him largely in his conclusions. These are in brief as follows:

"The popular belief is that devastating floods occur mainly in connection with melting snows, occasioned by heavy rains. The following notations may offer in part an explanation of the occurrence of the recent flood in absence of material snow-cover in the mountains.

"During a storm-period, when a substantial runoff occurs from heavy rains extending to high altitudes, from two to four feet of snow may completely disappear from a 1,000-foot altitude belt just above the snow-line as it was located at the beginning of the rain. This recession of the snow-line releases a large volume of snow-water over a limited area, but it will not be menacing if it occurs only at rather low or intermediate altitudes. The normally heavy snow-cover which prevails at higher levels, under such circumstances, will absorb a great amount of rainfall and thus restrict the runoff over a large proportion of the drainage-area constituting the potential flood-hazard. If, on the other hand, the belt of receding snow extends to comparatively high levels, the area of effective runoff is proportionately increased, largely because of the absence of the snow-mantle and its dampening effect on runoff. From this it is apparent that the higher the snow-line at the beginning of heavy, general rains, the greater the probability of occurrence of high water.

"Several factors have an important bearing on the situation, however, such as the intensity and duration of so-called warm rains and the depth and density of the snow-cover from intermediate to rather high levels. While it is true that water from melting snow is an important contribution to runoff, its ultimate effect on the flood-situation depends upon the width and elevation of the zone over which the snow-line recedes during the course of a general rain-storm, which determines the magnitude and extent of the effective runoff-area."

Floods in the Tahoe-Truckee Basin--There have been three floods of magnitude in the Tahoe-Truckee Basin during the last 40 years and a minor flood during the present season. There was doubtless a much heavier flood than these in 1862 when Clarence King writes in his "Rambles in the Sierra" that it was difficult to ford the streams flowing from the Sierra into the San Joaquin and that the San Joaquin and Sacramento rivers were joined together. At that time a portion of the clay-bluff at the north end of Lake Tahoe is said to have slid into the Lake. I understand that there is a mark on one of the old buildings in Sacramento showing the height to which that River rose. Possibly the report by N. R. Taylor, Meteorologist, United States Weather Bureau, Sacramento, on "Floods in the Sacramento and San Joaquin watersheds" published in 1913 will give you more definite data regarding winter snow-cover and waters. Joseph Gross, Consulting Engineer of Sacramento, has much data on flood-conditions and flood-causes in the Sacramento River. He has a paper on "Forest- and range-hydrology in relation to water-supply [Trans. Amer. Geophys. Union, 1938, pp. 619-629]. A very lively discussion arose at the Davis Meeting, where Mr. Gross spoke, regarding the causes of the flood of December, 1937.

Four floods of 1907, 1928, 1937, and 1940

Since some data are available on the four floods referred to, it seems best to present the material in case-form so that analysis can be made of temperature, snow on the ground, precipitation, and flood-peak. These floods are March 1907, March 1928, December 1937, and March 1940. The weather-stations are at Tahoe City (6,225 feet) or Truckee (5,819 feet) and the gaging-station of the Truckee River is at Iceland. The data are summarized below:

March, 1907--Truckee (5,819 feet): Snow on ground moderate; precipitation for January 8.85 inches, for February 2.30 inches, and for March 20.50 inches; mean daily flow of Truckee River at Iceland, March 18, 15,300 cfs (Professor H. P. Boardman suggests that this must have been the approximate crest); at Reno at 8 A.M. the river-flow was 14,700 cfs, but an hour later the level was one foot higher.

The peak appears to be a spire, judging from the record for March 17-20, namely, 3,740, 15,300, 8,500, 6,970 cfs. By March 23 the runoff had fallen to 2,400 cfs. The record is rated B or medium for accuracy. The record for Truckee, March, 1907, is as follows: Mean temperature 34°.2 F (departure +0°.8 F); precipitation March 1, 1.40 inches, and March 9-25, 19.10 inches fairly evenly distributed. Precipitation at Summit Station (7,000 feet) from March 1 to 26, total 27.36 inches with maximum daily precipitation 2.80 inches. There is no record of depth of snow on the ground at Truckee where melting should have occurred. At Summit Station the depth of snow on the ground increased from 104 inches on March 1 to 246 inches on April 1, indicating little rain at this elevation and probably no loss. Previous to the flood "spire" of March 18 a total precipitation of 10.84 inches (probably mostly snow) fell at Summit Station March 10-18 and 12.14 inches at Truckee March 9-18, with 3.10 and 3.60 inches at the lower elevation on March 17 and 18. This concentration of 6.70 inches within two days with 1.20 inches the day previous apparently caused the flood.

March, 1928--Tahoe City (6,225 feet): Temperature-departure for March, +3°.8 F; snow on ground March 15, 9 inches (water-content approximately three inches); heavy rain March 22-28, 10.17 inches; Truckee River crest at Iceland, March 25, approximately 15,000 cfs.

December, 1937--Tahoe City (6,225 feet): Temperature-departure for December, +4°.1 F; snow on ground December 1, trace; heavy rains December 10-12, 9.73 inches (rain at Truckee December 9-11, 6.78 inches); Truckee River Crest at Iceland, December 11, 15,600 cfs.

Runoff in quantity has never been found in these basins above the altitude of 7,000 feet. I well recall coming down from Mount Rose in a semi-chinook storm that swept the snow from the valley-floor and created very high water in the Truckee River. I do not now recall the year. But the snow-cover at that time retreated no farther upward than to altitude 7,000 feet. However, a slight erosion of Jones Creek at the foot of the canyon at this elevation indicated that some water had come from higher up. In 1937 during the rain- and flood-period mentioned above by Mr. Fletcher, the rain occurred at 9,500 feet and the snow-cover in the Truckee Canyon was reported as having been washed entirely away at 6,500 feet. The latter is not strange since at Tahoe City (elevation 6,225 feet) only a trace of snow was reported at the beginning of the month. The story is told by Wayne Paulsen in his paper on "Snow-surfaces in the high Sierras for skiing-purposes" [Trans. Amer. Geophys. Union, 1939, pp. 79-83]. He remarks:

"During the early part of the season, and, indeed, at any time during the season, rain sometimes falls in the high Sierras instead of snow. If the rain is heavy it may wash all the snow off the popular ski-areas or completely ruin the surface of the snow until the next snowfall. The elevation of the ski-fields in this case plays a large part. As a general rule, during the wettest seasons it will not rain above 6,500 feet. This is especially true from December to the first of April. However, occasional storms will wash all of the snow away as high as 10,000 feet. Rain will not only cause poor skiing-conditions, but will usually put ski-fields in a very dangerous condition.

"As an illustration, such a condition occurred on December 9, 1937, while Halvor Mikkelsen and myself were stationed at Rifle Peak (see Fig. 4). At 8 A.M., temperature 26°, heavy snow started falling, driven by a strong wind which had been blowing all night. The snow continued steadily all day with the wind lessening and the temperature rising. At 5 P.M. the snow became very wet and heavy with the temperature at 33°. At 9 P.M. the snow changed to rain with an increasing wind, temperature at 36°. It rained all night with a heavy wind, which came from the west and southwest during the entire storm. The wind and rain continued heavily all day and night of December 10. On December 11 the rain changed to snow at 8 A.M. with a little let-up of wind. It changed back to rain, however, after an hour. The temperature dropped from 36° to 34° when it snowed, but rose to 36° when it changed back to rain. The rain changed back to snow at 11:30 A.M. and continued all day with a decreasing wind. The snow was very wet and heavy, falling at temperatures ranging from 30° to 35°. After snowing all night, a new cover of only ten inches had fallen on the old pack which had been reduced from five to two feet. The new cover was very heavy and wet, making very difficult skiing-conditions.

"At 10 A.M., December 11, when we were certain that it would continue to snow, we started

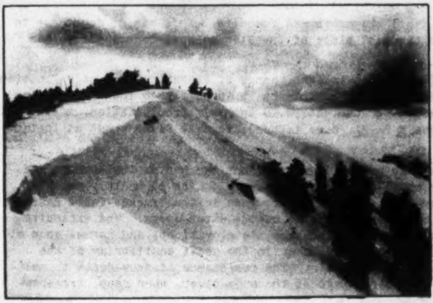


Fig. 4--Snow-cornices, head of Joe Gray Canyon near Rifle Peak, Lake Tahoe

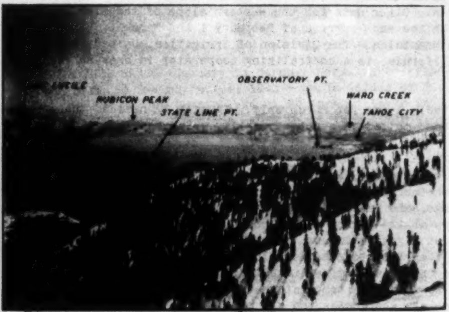


Fig. 6--Lake Tahoe from above State Line Point with snow-courses indicated along northwestern slopes of Basin (View from elevation 9,000 feet, land-surface elevation 6,225 feet)

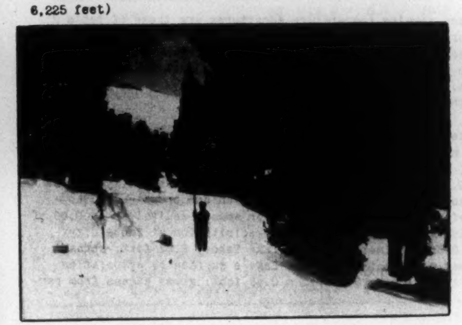


Fig. 7--Sampling at timber-line on Mount Rose (Snow is as deep as sampler is tall; total depth, 21 feet; this snow is impregnable to rápid melting)

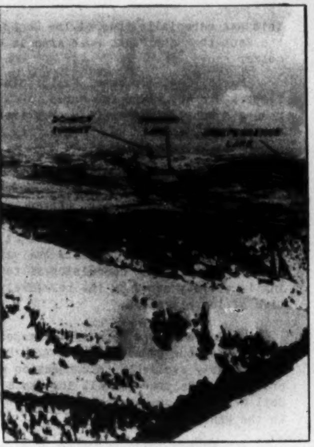


Fig. 5--Upper Truckee Basin from Mount Rose (Unlike Lake Tahoe, Donner Lake always freezes and here appears as a meadow; snow-courses are indicated; floor of Basin approximate elevation 6,000 feet)

on skis for Iceland down Joe Gray Canyon Canyon some ten miles distant on the Truckee River. This meant a drop of about 4,500 feet in elevation. Immediately we found that the snow was in a very dangerous condition to ski upon. Wet-snow avalanches had occurred on all sides of the Canyon. Although the walls of the Canyon were very steep, they had a great deal of natural anchorage and usually were very safe under most unusual conditions. Although we proceeded with the utmost caution, and skied several hundred feet apart, our weight on the new snow caused three big slides and several smaller ones. We regarded ourselves as being very fortunate in not being caught in any of them.

"The rain had washed most of the snow off below 6,500 feet in this particular area. This was the time of the flood in the Truckee River Canyon and the Sacramento Valley.

"The snow which followed this rain-storm left an average cover of four feet, the surface being a fine powder which made very good skiing-conditions. At this time, the snow was completely washed off most of the big ski-centers of California.

This was especially true of the Donner Trail ski-areas and Yosemite. This was no doubt due to the fact that the Mount Rose Area is on the east slope of the Sierras and, consequently, has colder snows."

March, 1940--Truckee, California (6,200 feet--slight change of elevation account relocation): Temperature-departure for March, +2°.3 F; snow on ground March 15, probably 40 inches (snow on ground March 1 at Tahoe City 43.9 inches, water-content 16.10 inches); precipitation, mostly rain, March 25-31, 6.16 inches (Tahoe City, March 25-31, 6.94 inches); Truckee River crest at Iceland, March 30, 7,120 cfs.

Fortunately the abnormally mild weather prevailing throughout the winter in the west and the occurrence of rains in place of the usual snow have caused the taking of monthly measurements of snow-cover at most of the lower-level snow-survey courses in the Truckee-Tahoe Basin which is now being carefully regulated by formal agreement of the water-users. The excessive rain at low elevations, the deficient snow-cover at intermediate elevations, and normal snow at the higher elevations indicate the varietion that may occur in the usual equilibrium of the snow-cover under the compulsion of temperature and rain. The resistance of snow-depth to melting is vividly shown by the relatively high percentage of the snow-cover, when deep, irrespective of low elevation.

In Table 1, the data are arranged by elevation for the Truckee and Tahoe basins and for portions of the adjacent South Yuba Basin. Other data for the western slope of the Sierra Nevada are probably available in connection with the snow-surveys of February 1 and March 1. This probably holds true for all the western mountains. The Division of Irrigation, United States Soil Conservation Service, Berkeley, California, is a centralizing cooperator in snow-surveying in the Western States.

The losses and gains indicated in Table 1 are for March only. It will be noticed that the snow of shallow depth or at lower altitudes melted in greater quantity. Sagehen Creek appears to be an exception.

But even the deepest snow and at high altitude, as at Lake Lucile, was not only ripe but was losing its water-content. One wonders whether the difference in percentage of precipitation at the base-stations of Truckee, Soda Springs, and Tahoe City, and at the crest of their watersheds means that rain and melting occurred even at the higher elevations. If so, the flood of March was supplied in part from above 7,000-foot altitude unless the soil held the melt-water in suspension. The quick fall of the peak of the flood to steadier flow proves that the water-movement was under restraint. The measurement of the snow-cover at Lake Lucile, April 15, would have given clue to the rapidity of melting. However, the temperature-departure for April 1-15 at Reno was only +3°.1 F. During March, the loss where measured was not large. The maximum in March, as at Upper Truckee River Course of snow-depth of 32.3 inches and water-content of 11.0 inches and mean temperature of 43°.5 F at Tahoe City, was 7.2 inches water-content. This melting was doubtless accelerated somewhat by rain.

Other measurements of melting under varying temperature-departures are those of Table 2 selected from April when the temperature is rising. The temperature of April, especially at high plus departures, should be representative of flood-temperatures in March and far above those of December--the months in which the floods studied occurred. The snow-courses selected are at Soda Springs and Summit Station. The temperature is the mean monthly at the former and thus represents actual conditions at the snow-fields.

Runoff--The effect of the midwinter loss of 22.25 inches from the precipitation of 33.25 inches has not been flood on the Lake nor on the shore.

On the measured relationship of 0.80 between the annual snow-cover at Tahoe City and the snow-cover around the edge of Lake Tahoe (6,225 feet) as determined on one occasion by snow-surveys, and the assumption that therefore the Lake should rise an amount equivalent to 0.80 of the precipitation there, its excess rise is as follows: Total precipitation at Tahoe City, 33.25 inches = 2.77 feet; at ratio of 0.80, estimated rise of Lake Tahoe, 2.22 feet; actual rise, 2.31 feet; excess over storm-rise, 0.09 foot; lost from Lake's surface by evaporation January to March, (1.60 + 1.75 + 2.00 inches) = 5.35 inches = 0.45 foot; gross excess from percolation, 0.54 foot.

Estimate of melt-water--The divergence between the total precipitation of 157.4 per cent of normal (December to March) at Tahoe City, 88.7 per cent at Ward Creek (7,000 feet), and 113.3 per cent at Rubicon Peak (8,100 feet) indicates that melting occurred during the winter over the entire watershed. This is borne out from the evidence of drip-water at Lake Lucile (8,400 feet)

Table 1--Snow-cover variation with altitude, March to April 1940

Elevation	Station	Date	Depth snow	Water-content	Density	Per cent of April 1 normal	Loss(-) or gain(+) from April 1 normal	
feet		1940	inches	inches			inches	per cent
TRUCKEE BASIN (Fig. 5)--January to March: Normal precipitation at Truckee (6,200 feet) = 13.61 inches; actual 1940 = 27.63 inches or 203.0 per cent of normal, excess = 14.02 inches								
6,400	Truckee No. 2	Mar 2	47.9	17.0	35.5	85.5		
		10	47.2	16.4	34.6	82		
		30[a]	35.2	12.7	36.1	63.5	- 4.3	-21.5
6,500	Sagehen Creek	Mar 5	49.0	17.7	36.1	80.5		
		Apr 1	39.9	16.6	41.8	75.5	- 1.1	- 5.0
6,500	Independence Creek	Mar 1	35.8	13.4	37.4	74.4		
		Apr 1	24.0	9.0	37.5	50.0	- 4.4	-24.4
8,200	Independence Lake	Mar 3	117.0	41.5	35.5	86.5		
		Apr 1	139.5	51.7	37.0[b]	107.7	+10.2	+21.2
7,000	Webber Lake	Apr 4	88.7	38.7	43.6	101.6	....	....
8,000	Webber Peak	Apr 4	131.3	52.4	39.9	92.1	....	....
8,200	Granite Peak	Mar 31	75.2	31.0	23.3	94.3	....	....
8,800	Big Meadows	Apr 1	72.0	44.0	31.7	112.8	....	....
SOUTH YUBA BASIN--January to March: Normal precipitation at Soda Springs (6,752 feet) = 24.56 inches; actual 1940 = 53.28 inches or 216.9 per cent of normal, excess = 28.72 inches (March 1-24, 1.24 inches; March 25-31, 11.61 inches); temperatures March, 1940: Maximum, 45°.7 F; minimum, 16°.9 F; mean, 31°.3 F								
6,500	Fordyce Lake	Mar 4	89.0	35.9	40.3	70.4[c]		
		Apr 2	86.4	36.1	41.8	70.8[c]	....	+ 0.4
6,500	Furnace Flat	Mar 5	104.5	44.1	42.2	74.7[c]		
		Apr 2	113.0	45.0	39.8	76.3[c]	....	+ 1.6
7,000	Summit Station (near Ry) (Including Summit Valley also)	Mar 1	116.9	43.0	36.8	90.0[c]		
		Apr 1	112.9	48.6	43.0	101.7[c]	....	+11.7
LAKE TAHOE BASIN (Fig. 6)--January to March: Normal precipitation at Tahoe City (6,225 feet) = 17.33 inches; actual 1940 = 33.25 inches or 191.9 per cent of normal, excess = 15.92 inches								
6,225	Tahoe City	Mar 1	43.9	16.1[d]	36.7	101.3		
		Apr 1	24.9	11.0	44.2	69.2	....	-32.1
6,225	Camp Richardson	Mar 2	35.5	11.8	33.2	73.7		
		30	19.9	6.7	33.7	41.9	....	-31.8
6,400	Upper Truckee River	Mar 3	32.3	11.0	34.0	100.0		
		31	11.4	3.8	32.9	34.1	....	-65.9
6,700	Glenbrook	Mar 2	51.8	12.2[e]	23.6	87.1		
		30	33.1	10.5	31.8	75.0	....	-12.1
7,000	Ward Creek	Mar 3	119.4	44.2[f]	37.0	86.4		
		Apr 6	116.0	52.7	45.4	88.7[g]	....	+ 2.3
7,300	Freel Bench	Mar 3	42.2	13.4	31.7	89.4		
		31	23.3	8.7	37.4	58.0	....	-31.4
7,350	Daggetts Pass	Mar 2	49.8	15.4	30.9	94.5		
		30	34.9	13.9	39.8	85.3	....	- 9.2
8,000	Hagan's Meadows	Mar 31	50.7	19.0	37.6	89.6	....	....
8,000	Marlette Lake	Mar 1	91.2	30.1	33.0	108.3		
		Apr 1	81.3	33.7	41.5	121.2	....	+12.9
7,500	Rubicon Peak Lower or No.2	Apr 7	86.4	38.3	44.3	95.8		
8,000	Upper or No.1	Apr 7	145.0	55.4	38.2	113.3		

Table 1--Snow-cover variation with altitude, March to April 1940--Concluded

Elevation	Station	Date	Depth snow	Water-content	Density	Per cent of April 1 normal	Loss(-) or gain(+) from April 1 normal	
feet			inches	inches			inches	per cent
LAKE TAHOE BASIN (Fig. 6)--Continued								
8,400	Lake Lucile	Apr 1	184.6	69.3	37.5	113.2		
	[Notes: Survey was made during a snow thunder-storm. Depths of 200 inches were found. Snow-cores settled 20 to 30 inches. Snow-densities were 40 to 43 per cent. Snow was water-soaked. Water would drip from snow-samples. There were snow-crusts but none of ice. No adhesion of snow to sampler; cores slid out of tube when tapped.]							
9,000-10,800	Mount Rose (Fig. 7)	Mar 31 -Apr 1	96.7	40.2	41.6	89.3		

[a] On March 30, snow-cover on way to Truckee No. 2 had two-inch slush on ice-crust; snow below crust rain-soaked. [b]"Could squeeze water out of snow; packed like 'water-soakers,' that is, wet snowballs; noticeable voids between crystals; water gone through." [c]Normal = 47.0 inches at Summit Station, based on Truckee Basin flow; others based on Truckee also. [d]Normal April 1 = 15.9 inches. [e]Normal April 1 = 14.0 inches. [f]Normal April 1 = 51.2 inches. [g]Adjusted; an avalanche buried the course nearer the base of Ward Peak; slope exposed to Sun; snow-slides rare at Tahoe; a major slide crossed Truckee River Canyon.

Table 2--Rates of melting of snow in April at 7,000-foot altitude

Item	1936		1937		1938		1939	
	Summit	Soda Sp.	Summit	Soda Sp.	Summit	Soda Sp.	Summit	Soda Sp.
Snow-depth								
April 1, inches	97.8	94.8	109.3	110.5	162.4	153.7	59.6	52.8
May 1, inches	70.8	61.7	70.4	70.8	121.0	110.3	0	0
Loss, inches snow-depth	27.0	33.1	38.9	39.7	41.4	43.4	59.6	52.8
Water-content								
April 1, inches	48.5	43.8	43.0	44.2	68.7	62.6	25.0	21.5
May 1, inches	34.4	32.4	36.5	36.7	59.2	55.4	0	0
Loss, inches water-content	14.1	11.4	6.5	7.5	9.5	7.2	25.0	21.5
Temperature-departure, °F, at Soda Springs, April (normal temperature 35°9 F)	+0.5		-4.5		-2.0		+6.0	
Precipitation April, inches	3.21		3.35		2.95		0.34	

on April 1. However, the low percentage of 89.3 on Mount Rose (9,000 to 10,800 feet) where melting could scarcely have occurred indicates that the actual precipitation at the higher elevations was relatively less than at the lower. There is, however, no doubt that melting occurred at elevation 7,000 feet, for high water was reported in the South Yuba immediately below Soda Springs (6,752 feet). This was accentuated by the rock-floor of the Basin which permits only slight percolation.

In case a loss of 22.25 inches had occurred as high as 7,000 feet, which is extremely doubtful, the deep granite-sand of the Tahoe Watershed should have moderately delayed its flow. Since the land-area of the Tahoe Basin below 7,000 feet is 128.5 square miles as compared with 192.7 square miles for Lake Tahoe itself, or only 2/3 (66.68 per cent) as great, the equivalent rise of the Lake from this source would be 14.86 inches or 1.24 feet. However, if this runoff is confined to the zone below 6,500 feet, which seems more probable, the ratio of land-surface to lake-surface would be 70 square miles to 192.7 square miles or 1/3 (36.3 per cent). The equivalent rise would thus be 8.08 inches or 0.67 foot.

The streams feeding Tahoe probably did not flow a total of 400 cfs during the three months or an equivalent of 0.6-foot rise on the Lake. One day (sky overcast) in March, the only day of observation, the total flow was estimated at only 200 cfs. The soil on this day was wet to a

Table 3--Precipitation and melting at Tahoe City (6,225 feet), January 1 to March 31, 1940

Date	Precipitation		Snow-residue		Percolation or run-off	Rise, Lake Tahoe	Ratio, rise to precipitation during storm-periods
	Kind	Am't	Am't	Dens.			
1940		inches	inches		inches	feet	
Jan 1	Snow-cover	.....	0.00	....	.....	....	....
1-31	Rain and snow	13.50	.....	....	.....	1.03	Jan 1-13, 0.90 23-27, 0.965
Feb 1	(Snow-survey)	.....	7.70	39.5	5.80	....	....
1-29	Rain and snow	11.96	.....	....	.....	0.76	Feb 1-7, 0.67 14-18, 0.66 23-29, 0.91
Mar 1	(Snow-survey)	.....	16.10	36.7	3.56	....	....
1-31	Rain and snow	7.79	.....	....	.....	0.52	Mar 24 - Apr 1, 0.897
Apr 1	(Snow-survey)	.....	11.00	44.2	12.89	....	....
Totals							
Jan 1-Mar 31	....	33.25	.....	....	.....	2.31	Jan 1 - Apr 1, 0.83
Mar 31	(Snow-survey)	.....	11.00	....	22.25	....	....
Jan 1-Mar 31	(Normal)	17.33	.....	....	.....	....	Normal 0.80
Mar 31	(Normal snow-survey)	.....	15.90	....	1.43[a]		by snow-survey methods (storm-periods)

[a] Residue on basis of precipitation December to March instead of January to March, 5.99 inches.

depth of 3 1/2 feet. The actual rise of Tahoe corrected for evaporation appears to be reasonably near expectation. If the maximum loss of 22.25 inches occurred, the water is probably still seeping slowly through the soil.

Further study will be made of the relationship of the precipitation in the Tahoe Basin to the rise of Lake Tahoe. It is especially desirable to test the uniformity of seasonal percentage of snow-cover on the western and eastern sides of the Lake; also the ratio of the rise of the Lake to individual storms throughout the period of record. Theoretically the ratio as already mentioned is 0.80. Professor Boardman has used the ratio of 0.75. It will be noticed in the tables that the present year the ratio has varied from 0.66 to 0.965, the difference possibly being due to runoff during the period of precipitation. Naturally the runoff-ratio for the entire season would be lower because of the heavier evaporation occurring between storms.

The present year of 1940 is opportune. In the western States the season has been admittedly mild, with high snow-line and "highest flood-crest on record of the Sacramento." In the eastern States, particularly New York and Pennsylvania, an unusually cold winter has permitted the accumulation of a deep snow-cover. The flood of early April was not as high as in 1936. There was some frost on the upper Susquehanna, perhaps because of the intense cold. However, judging from measurements at Cranberry Lake in the Adirondacks, the frost under the snow is not deep, but offsetting this is the shallowness of the soil and the presence of slate-formation on much of the Susquehanna Watershed. We do not have at hand the record of the precipitation that evidently caused this flood. Probably the snow-cover controlled the runoff somewhat rather than accentuated it. Dr. Robert E. Horton has observed that floods in New York seldom occur when the snow is deep, as was the case the present year.

In the west there is little frost, for the soil at the higher elevations in the autumn drains dry. Deep soil or fissured rocks are frequent. Occasionally there are tight rock-basins such as that of the South Yuba. In the Pacific northwest frost may exist providing the temperature is sufficiently low. The floods therefore must be mainly the result of intense rains accentuated by snow if not too deep to be a deterrent.

Possibility of a still higher flood-crest in 1940 hinges upon the question whether the saturated snow on the watershed could have broken down still more into melting water. The temperature could have been higher and the precipitation could have been more intense. But the higher the elevation of the snow, the less it melts and the more it evaporates. Above 10,000 feet the "eternal" snows have little runoff but vanish in water-vapor.

The Humboldt flood of 1910--The rainless flood in the Humboldt Basin, Nevada, occurred in February to March, 1910, as the result of a cold winter of precipitation, varying from 82 to 135 per cent of normal, that accumulated, however, in the form of snow over the entire surface of the Watershed and was carried out by a maximum temperature on the floor of the Basin of 46° to 67° F extending beyond a period of 18 days when the crest reached the foot of the River. Minimum temperatures of 27° to 44° F occurred during the first six days that started the flood but during the remainder of the period never fell below 31° F.

Because of the desert-character of the region the soil was too dry to freeze. Furthermore, the bottom-lands are deeply alluvial. Snow two feet in depth (approximately 6 inches water) was reported in the valley-bottom and was probably twice that amount at 7,500 feet, the extreme upper level of melting.

The United States Weather Bureau reported: "During the warm weather of the last two days of February and March 1, 1910, melting snow swelled the Humboldt River, Nevada, beyond the highest stage known in 20 or 25 years.

"The older Indians around here claim that the snowfall of the past winter was the heaviest that ever occurred in their recollection. The Humboldt River was over six miles wide in places, flooding ranches and drowning hundreds of cattle and other animals.

"The Nevada Central track, from Austin to Battle Mountain, was entirely washed away, and it can not be made passable within two months."

Unfortunately no stream-measurements were made this year. The hydrologic record was lost and the phenomenon has not since been repeated. Only the recollection of the writer, aided by records of the engineers of the Southern Pacific and Western Pacific railroads, brought the event from oblivion. The stream-flow record for that year had been interpolated as subnormal by the hydrographer who came to the region following the event.

The weather-data are given in detail in Table 4 for the sake of the record. Fuller data and description are given in Climatological Service of the United States Weather Bureau, District No. 10, March 1910.

Table 4--Data for flood of February to March, 1910, in Humboldt Basin

Station	Month	Temperature, °F				Precipitation, inches			Snowfall unmelted, inches
		Mean	Departure	Maximum	Minimum	Total	Departure	24 hours	
Elko	Jan	17.2	-5.5	50.0	-28.0	0.43	+0.91	0.36	15.2
	Feb	24.4	-3.9	56.0	-14.0	0.84	+0.17	0.26	9.0
	Mar	43.8	+7.4	78.0	22.0	0.60	-1.14	0.06	T
Totals						1.87 (41.5 o/o normal)			24.2
Winnemucca	Jan	20.0	-8.8	47.0	-15.0	0.76	-0.28	0.60	9.2
	Feb	27.3	-6.0	55.0	-15.0	0.89	-0.04	0.44	9.4
	Mar	48.1	+8.5	72.0	28.0	0.24	-0.71	0.08	0.3
Totals						1.89 (47.5 o/o normal)			18.9 = (2.1 of water)

Comparative normals of precipitation with elevations (December to March): Winnemucca (4,344 feet), 3.98 inches; Elko (5,079 feet), 5.01 inches; Lamoille (6,100 feet), 7.75 inches; Lamoille Canyon (7,400-7,600 feet), 12.76 inches, (9,000 feet), 29.48 inches, the measurements in Lamoille Canyon representing the water-content of the snow-cover March 1.

The precipitations for period December to February, which provided the flood, were: Elko-Wells, 2.92 inches = 82 per cent; Winnemucca, 4.09 inches = 135 per cent of normal for the period.

Table 5--Daily temperature at Winnemucca, February 20 to March 15, 1940

Date	Maximum	Minimum	Remarks
1940	°F	°F	
Feb 21	39	28	
22	40	25	
23	46	31	
24	49	33	
25	47	28	Reported river rose at Winnemucca two feet during day; washout on railroads
26	39	27	
27	47	32	
28	55	44	At Battle Mountain; "Sudden thaw accompanied chinook wind"
Mar 1	60	39	Wave of high water at Palisade Canyon
2	67	32	
3	66	32	
4	65	32	
5	62	36	
6	65	32	
7	65	31	Crest of flood at Golconda
8	61	31	Maximum at Winnemucca
9	55	32	
10	60	31	
11	64	33	
12	65	35	Crest at Lovelock
13	72	36	
14	67	40	
15	63	35	

The Palouse River flood--The synchronous flood on the South Fork of the Palouse River in southeastern Washington, mentioned as a project at Bonneville, seems to have been made possible by the same cold winter and accumulating snow that affected the Humboldt. The only variant is a "one-day rain." A study of the weather and runoff of the interlying streams should be fruitful.

A desert-flood--That floods and flood-peaks are individual is shown by the "flood on the desert New Year's Day, 1910" in southern Nevada which concentrated in the narrow box-canyons of the Meadow Valley Wash and almost completely obliterated 83 miles of the San Pedro, Los Angeles, and Salt Lake Railroad (consequently rebuilt on higher ground).

The following meager weather-record that could be accumulated gains emphasis only from narratives such as the following:

St. Thomas, Nevada: "We had our first snow for 20 years, and the warm weather, winds, and rains that occurred in the last of December and the first of January caused the largest body of water to flow down this Valley any resident has ever known."

Overton, Nevada: "The snow was the first I have seen in Moapa Valley, and was more than any of the old residents here have ever seen."

Beaver, Utah: "Rain fell as high as the 8,000-foot contour on January 1, 1910, and to say there was a world of water puts it mildly. Every draw, hollow, stream, and drainage-course was filled to its fullest carrying capacity, as the slopes had been covered with about 12 inches of snow, and in the hills it was much deeper. A fortunate freeze on the night of January 1 solidified everything again."

Table 6--Data for flood of December, 1909, to January, 1910, in Colorado Basin

Month	Station	Temperature, °F			Precipitation, inches				Total snowfall unmelted, inches
		Mean	Maximum	Minimum	Total	Departure	Max. in 24 hrs	Date	
1909									
Dec 1	Wells	....	....	....	1.65	+0.62	0.40	..	16.5
-31	Elko	15.0	-12.0	-20.0	....	....	....	..	....
	St. George, Utah (2,880 feet)	....	52.0	-17.0	1.93	....	0.21	30	....
	Las Vegas (2,033 feet)	....	....	....	1.05	....	0.15	31	15.0
1910									
Jan 1	St. George, Utah	....	56	33	0.49	....	0.30[a]	1	....
2		....	38	32			..	..	....
3		....	41	27			..	..	....
4		....	34	26			..	..	....
5		....	30	16			..	..	....
6		....	31	12			..	..	....

[a] Total December 30, 1909, to January 1, 1910, 0.88 inch.

Note the cycle of heavy snows, cold spell, high temperatures, heavy rain, cold.

U. S. Weather Bureau comment: "On the morning of January 3, as the low pressure center moved off to the southeast, the rain turned to snow, with a cold northwest wind, and the temperature dropped to near, or below, zero, stopping the floods almost as quickly as they began, but leaving the hills bare and brown."

This flood would have been disastrous had it occurred elsewhere than in the sparsely settled desert.

Nevada Agricultural Experiment Station,
Reno, Nevada

DISCUSSION

MAJOR R. H. ELLIOTT (U. S. Engineer Office, Bonneville, Oregon; communicated)--Thank you very much for your long letter covering floods resulting from melting snow. The information contained therein has helped to give us a much better idea of the conditions which will produce large floods as a result of melting snow.

An engineer who has resided for several decades in the region of the Weiser River Basin located in southwestern Idaho, states that large floods in that Basin result from a combination of rain and a chinook-wind melting one to two feet of loose snow between elevations 2,100 and 5,000 feet. The snow in the higher reaches contributes no water to these floods, but furnishes irrigation-water during the growing season. This, I believe, is in complete agreement with your idea as to the conditions which produce the larger floods.

In regard to your request that this Office prepare a paper covering floods resulting from snow-melt in the Pacific northwest to be presented at the meeting of the American Geophysical Union in Seattle during June, 1940, would advise that our present information on the subject is not sufficiently mature to warrant this. Perhaps at some time in the future we may be able to prepare a paper presenting whatever information of value has been determined. Furthermore, we are handicapped because snow-course records for this Region are very limited.

Once again let me thank you kindly for your very informative letter. A representative of this Office will be present at the meeting of the Union in Seattle in order to obtain additional information on floods produced by melting snow.

L. STANDISH HALL (East Bay Municipal Utility District, Oakland, California; communicated)--The statement in your letter that the snow at the higher altitudes is practically impregnable to sudden melting agrees with my observations, particularly after January. In some instances a light fall of snow in November and December has been melted by later warm rains, but after

January, the principal danger of floods comes from the occurrence of large quantities of snow on the watershed at lower altitudes; in fact, any snow below an altitude of 6,000 feet constitutes a possible flood-menace. The very large floods, such as occurred in the winter of 1861-62, are the result of melting of snow which has previously been deposited at very low altitudes. No doubt further study on this subject would yield much information of value in the forecasting of floods.

UNIT-HYDROGRAPH

R. H. Elliott and LeRoy K. Sherman

[This paper is the result of correspondence between the authors--the first designated by (a) and the second by (b)]

(a) In connection with flood-control work here in the Pacific northwest, we meet with numerous streams having drainage-basins with variations in altitude ranging from 2,000 to better than 10,000 feet. Because of the amount of snow stored at the higher elevations, it is impossible to select a near unit-storm free from the effect either of snow falling or melting at the higher altitudes. So far, the only method we have been able to use on these drainage-basins for estimating maximum possible floods is that of Allen Hazen.

The graph of Figure 1 [p.953] shows the relation between temperature, precipitation, and runoff on the higher portion of the Payette River Drainage-Basin in southwestern Idaho and gives a concrete example of the problem involved (runoff shown is greatest for 30-year period). Although the Drainage-Basin in this case has an area of 2,230 square miles, there are only three Weather Bureau stations in the Area, the highest being at an elevation of 5,025 feet.

Can you make any suggestions or give us any references or other information that would assist us in applying your unit-hydrograph method to this type of drainage-basin? In any event your comment will be appreciated.

(b) Referring to the application of the unit-graph method for estimating floods from snow-melting, until the unit-graph had been thoroughly tested in application to runoff from rainfall, its use was not encouraged for snow-melting. The unit-graph has now become standard practice for the rainfall-runoff relation, and the following are my first thoughts in writing relative to its application to snow-melting.

The unit-hydrograph reflects the stream-flow due to a volume of surface-runoff contributed in a unit of time. For example, one inch of effective, or net, rainfall over a basin of 100 square miles, is a volume of 100 inch-miles or 2,689 cfs-days. If this volume of net rainfall occurred in, say, 12 hours, it would produce a 12-hour unit-hydrograph of runoff in the stream at the outlet of this basin. This total volume of this hydrograph would also contain 100 inch-miles. The duration or base of the hydrograph, and the peak-rate and other rates of flow of this unit-hydrograph, would be typical for the observed percentage-distribution of stream-flow on this basin.

If, in the 12 hours of unit-time, only one-half inch of net rainfall occurred, the ordinates would be one-half as much, but the time-base would be the same. If there were two inches of net rain, the ordinates would be twice as much, but the base of the unit-hydrograph would still be the same for all three cases.

If the net rainfall for these three cases of 12-hour periods occurred consecutively, in 36 hours, the resultant stream-hydrograph would be furnished by the typical summarization-procedure for unit-graphs.

All of the foregoing is common knowledge in the field of rainfall-runoff relations. If snow-melting produced water, in excess of infiltration and evaporation, amounting to one inch, one-half inch, and two inches, in three successive 12-hour periods, the resulting hydrograph of stream-flow would be exactly the same as the foregoing hydrograph from rainfall for 36 hours. This is assuming, of course, that the river-channel is not obstructed by ice, and further assuming that the contributions of one inch, one-half inch, and two inches reached some stream-channels within the 12-hour unit-time. Therefore, fundamentally, the unit-hydrograph may be applicable to the same percentage-distribution graph resulting from rainfall-runoff.

We have been speaking about water which reached the stream-channel or upper rivulets. In that volume of one inch of water from snow-melting in 12 hours, may, or may not, be the same contribution to the stream as the net volume of one inch of rainfall. The phenomena of overland-flow is not the same in the two cases. The snow-blanket on the surface of the ground may delay runoff and increase surface-detention, thereby making the period of surface-runoff and amount of runoff at some rate different from the rate of water furnished by rainfall. This relationship between snow-melting and surface-runoff has been studied by a number of specialists engaged in the hydrology of snow. I am not particularly qualified as an expert in this detail of hydrology, and I am referring it to some of my associates who are snow-experts.

The unit-hydrograph with this relation between the time of snow-melting and surface-runoff may be developed into runoff in time-units. When this is done, the unit-hydrograph may be applied. Whether the unit-hydrograph will furnish a better tool for forecasting than the present more-or-less empirical applications provide, is now a matter that should be tried out and tested, particularly by men who are acquainted both with the unit-hydrograph and the phenomena of snow.

The following list؛ authors who have papers in the "Transactions of the American Geophysical Union" relating to estimates of runoff and stream-flow from snow-melting:

1936: Articles by Clyde, Cullings, Elges, and Lee
1937: Articles by Farrow and Marr
1938: Articles by Farrow, Matthes, and Paget
1939: Articles by Elges and group-symposium
1939: Article by Clyde [an abstract of paper in "Civil Engineering," dated April, 1939]
See also paper by Bertram S. Barnes in Bull. Amer. Met. Soc., April, 1940, p. 95, for phenomena of runoff from snow and snow and rain.

U. S. Engineer Office (R.H.E.),
Bonneville, Oregon
58 West Jackson Boulevard (L.K.S.),
Chicago, Illinois

ICE IN THE NORTHERN STREAMS OF THE UNITED STATES

Walter J. Parsons, Jr.

Much has been observed and written about the open-summer phase of river-behavior, little about the winter phase. This paper will attempt to describe objectively some of the less well-known phenomena of the winter phase of a river's annual cycle.

The freeze-up--With the coming of cold weather, the water gradually is cooled, its temperature being intermediate between the cold air on the surface and the warm rock of the river-bed that still retains the heat of the summer. Within the mass of the water, temperatures tend to be uniform, the water being continually stirred by turbulent currents. This uniformity is further aided by the sinking of the cold, dense surface-layers and the welling up of the warm, lighter bottom-layer. Occasionally temperature-stratification occurs in deep, quiet pools. The water cools degree by degree until the entire mass is close to the freezing-point. Finally, the surface-film of water is cooled below the freezing-point and suddenly changed into needle-like crystals of ice that are slightly lighter than water.

The degree of turbulence compared with the rapidity of freezing now causes the ice-formation to follow one of three general courses. In Case I, when turbulence is large, the crystals are carried below the surface and the entire body of water is converted into a milky mixture of ice and water. This is called "frazil ice" and causes considerable trouble at power-plants and control-gates. When the floating crystals touch any surface that has a temperature even a fraction of a degree below the freezing-point, such as the submerged portion of a steel rack or a mass of sheet-ice, the crystals instantly adhere and form a spongy, rapidly growing mass that can quickly choke even large waterway-openings.

In Case II, when turbulence is less, the crystals remain floating on the surface, touch, interlock into a loose network, form little floating islands that join, are crushed together, and grow larger. Within the open meshes of the network, the liquid water is trapped and cannot easily mix with warmer subsurface water. It therefore freezes rapidly and unites the network into solid pans of ice. These pans are carried downstream until they touch the cold shore, freeze tight, catch other pans, and so jam from shore to shore. This is the end of free flow in the river. Floating pans strike the jam and rapidly extend it upstream, submerged crystals of frazil ice are carried under the ice-bridge and floating upward, adhere to the bottom-surface and thicken it. Soon the whole reach of river is solidly covered. In Case III, with still less turbulence, the floating nets of crystals unite without crushing and crystal-growth in the interstitial water unites the mass into a clear sheet of "rubber-ice."

Upon the creation of a continuous ice-cover, the freezing process enters a new phase. Heat can no longer be lost by radiation directly from the free water-surface to the cold air, but must be carried by conduction through the ice-layer. Since ice is a poor conductor of heat, the temperature-gradient is steep and the rate of freezing from the bottom surface of the ice rapidly decreases as an inverse exponential function. Normal winter temperatures in the northern States rarely can freeze single sheets of river-ice more than 30 inches thick. When there is a snow-blanket on top of the sheet-ice, the conduction of heat is still further reduced and the rate of freezing is correspondingly decreased. The end-result of the process is a dense watertight sheet of floating ice with its temperature ranging from a fraction of a degree below freezing at the bottom surface to air-temperatures of from freezing to as low as -60° at the top surface.

At this point, it is proper to describe an abnormal type of ice-formation called "anchor-ice" that occurs in clear swift streams with dark rock-bottoms. On cold, clear nights the dark rocks of the bottom lose heat so rapidly by radiation up through the water into the sky that they cool below the freezing-point of water above them. The adjacent water is frozen into transparent "skull-caps" as much as two inches in thickness, firmly attached to the rocks. The effect on the river-flow is the same as if the bottom had suddenly risen one or two inches throughout. When daylight comes, the sunshine penetrates through the clear water and transparent anchor-ice to the dark rocks and warms them up. The anchor-ice is melted loose and floats up to the surface. The result is, that shortly after sunrise, there is a sudden increase in the amount of floating ice and trouble due to clogging of gates and racks becomes acute.

Another abnormal phenomenon is associated with the thickening of the original ice-cover. It has been observed that during a prolonged cold spell when the air-temperature remains continuously below 0° F, the rate of thickening of the original ice-cover decreases at an abnormally rapid rate. When, on the contrary, the low temperature fluctuates enough to approach the freezing-point, the ice thickens at a normal rate. A possible explanation of this phenomenon lies in the theory that liquid water is a mixture of several molecular forms of H_2O, only one of which can change into solid ice. At temperatures well above freezing, the forms maintain their normal proportions by continuous interchange of form. As the freezing-point is approached, the speed of interchange is greatly slowed down. During a prolonged cold spell, the ice-making form is soon exhausted and further ice-making is delayed until this form can be replenished from the other forms. Fluctuating temperatures permit the maintenance of normal proportion of the different forms.

Effect of ice on river-flow characteristics--Although the viscosity of water increases with decreasing temperatures, the effect on the normal turbulent flow of water in natural rivers is rarely large enough to be observed by current-meter measurements. The retarding effect of suspended frazil ice or floating pan- or slush-ice is likewise small. With the formation of a complete ice-cover solidly anchored to the banks, flow-conditions change radically. The depth of the ice below the free water-surface has been subtracted from the area available for flow, and, in addition, the under surface of the ice acts as an additional friction-surface. The free water-surface (which is what is ordinarily measured by river-gages) may have to rise as much as four feet, in extreme cases, to pass the same flow as before the formation of the ice-cover. At first, the under surface of the ice is rough with many projections formed by the protruding edges of pans of ice that were turned on edge as they jammed together. Rough porous masses of frazil ice are caught under the ice-sheet and greatly obstruct flow. The sudden increase in stage throughout the channel requires the storage of large volumes of water. As a result, the river-flow temporarily decreases. When the additional storage has been satisfied, the flow returns to normal. This sudden decrease and recovery is a sure indication that the upstream reaches of a stream have changed to the winter phase. Within one or two weeks, the reduction in heat-loss arising from the insulating effect of the ice-cover permits the temperature of the water to rise sufficiently to melt the masses of frazil ice and projecting slabs of ice below the solid ice-cover. The under surface of the ice becomes smooth as glass and almost plane. Flow-conditions are improved and stages slowly drop, releasing part of the stored water. Near stable conditions now exist with the only change the slow increase in stage as the ice-cover gradually thickens.

Behavior of ice in mid-winter--The ice-cover is normally in a state of almost complete flotation. The edges of the ice-sheet are frozen solidly to the banks and to projecting boulders and bridge-piers, but the stiffness of the ice against cross-bending is so small that within a distance equal to about ten times the ice-thickness, the ice is at the normal flotation-level. Rising stages lift the center of the ice-sheet but leave a depression along the shore that may be below the free water-surface. In that case, the depression soon fills with water from melting snow or through cracks in the ice and the next cold spell freezes the water, restoring the level upper surface of the ice. On rare occasions, a stream-bed is so narrow between projecting boulders that a sudden decrease in flow will cause the water to drop completely below the ice, leaving the ice temporarily suspended and the water flowing free inside a tunnel. This condition does not last for long before the ice cracks and falls back to normal flotation-level.

Ice expands and contracts with temperature-changes in the same way as rocks, although the presence of water in contact with the under side reduces the range of temperature. Rising temperatures cause expansion that exerts outward pressure toward the banks. Normally, there are enough weak points in the ice-sheet to permit the release of this pressure by buckling of the ice-sheet or crumpling of the edges of the sheet. Occasionally, the temperature-rise is so rapid that enormous expansive pressures are developed at the edges of the ice,and exposed piers, bulkheads, or sea-walls are overturned or shoved bodily. When the expansion is less rapid, the ice has time to adjust itself at weak points by crumbling and internal shear so that little damage is done. Sometimes the entire frozen surface of the river-bank, including rocks, earth, and sand are sheared free from the unfrozen sub-soil and piled up in characteristic long ridges parallel to the stream-channel. This action on mid-channel sand-bars is to pile them up above water-level.

Similarly dropping temperatures cause contraction of the ice-sheet. Since ice is very weak in tension, the stress is easily released by numerous tension-cracks. The ice-sheet already shoved up on the bank is not retracted but remains perched on the bank. Contraction of ice is usually harmless to engineering structures. However, the combination of alternate expansion and contraction causes a ratchet-action that is more severe than either action separately. Since contraction takes place during colder temperatures, the water that rises in the tension-cracks freezes at once, filling and sealing the cracks. When temperatures rise again the cracks cannot close and the entire expansion must take place at the edges of the sheet. Similarly, compression-cracks (caused by buckling) freeze solid and are stronger than before. Each cycle of contraction and expansion shoves the edges of the sheet farther up the bank.

Piers or walls exposed to the full force of ice-expansion are usually protected by maintaining a belt of open water in front of them. As new ice freezes in the open lane of water, or as ice-expansion closes it, this protective belt must be reopened and the ice-cakes removed. Recently a clever use has been made of the residual heat of the water under the ice. A perforated air-pipe is placed along the bottom of the river in front of the wall or gate. The rising air-bubbles drag warm bottom water upward and cause active circulation that prevents surface-freezing and even melts heavy sheet-ice that has been shoved into the protecting lane.

Thawing of river-ice--When winter comes to an end and air-temperatures rise, the ice-sheet begins to melt. The water beneath the ice has always been warmer than the ice, but now the insulating snow-blanket is melted away and the Sun beats down on the bare upper surface. Solid clear ice melts very slowly. I have seen massive cakes of ice three feet thick which were solidly frozen to the face of steel gates remain frozen in place for as long as 48 hours after they had been deeply submerged by lowering of the gate, although the ice was surrounded by swiftly moving water passing through the open gate. However, in favorable locations, the snow-melt water on top of the ice carries heat down every crack in the ice and the once solid water-tight mass is transformed into a honeycomb-structure of long crystals normal to the surface which occupy the same total volume, but which is structurally weak and has its pores filled with water. To the casual eye, the ice looks as solid as it did in January, but actually it has changed radically. Then comes the first spring rise in the river. The snow-melt water from the hillsides enters the stream, the flow increases and the stage rises, the ice-sheet is broken loose from the banks and the cracks are not resealed with fresh ice. Then one day comes that ever-fascinating sight, the ice-run. A weak section of ice floats free of its anchorage and releases the water stored above it. This extra water floats the next section free, releasing more stored water. All at once, the whole river begins to move, the apparently solid cakes crumbling into slush as they strike the bank and against each other. A few ice-cakes from shaded locations are still hard and strong. Armed with gravel and boulders frozen into their bottom, they crash on bridge-piers and grind timber-cribbing to match-sticks. However, the great majority of the ice disintegrates into slush that melts while you watch it. The next day, the river is running clear from bank to bank with only a solitary ice-cake piled up here and there on a sand-bar.

U. S. Engineer Office,
Sacramento, California.

DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--I feel that we have in Mr. Parsons a return to the John Burroughs type of scientist, who sees and enjoys nature as romance and truth. May the type grow larger!

In Greenland the ice on rivers and lakes grows in the winter to a maximum of approximately four feet in thickness but melts in the summer. On Watson River in inland coastal Greenland the ice was arched completely across the river-channel so that the latter could be identified and followed by the convex surface. So pronounced was the curvature that unless one walked astride of the apex he would slide downward as on a roof.

The river beneath the ice was completely dry and the whirlpool cataracts, which terrified in the summer, were now a giant's staircase up which packers threaded their way among massive boulders.

The banks of lakes, when consisting of tundra, were found torn loose with wide cracks evidently from ice-contraction.

Of two neighboring inland fiords, one was frozen throughout the winter and the other remained open, thus necessitating on the spring trip to the coast a shift from sled to boat. This is an interesting side problem on a trip to the Arctic.

WINTER OVERFLOW FROM ICE-GORGING ON SHALLOW STREAMS

J. C. Stevens

A peculiar phenomenon of ice-gorging may occur during periods of low temperatures in alluvial valleys where the river has comparatively low banks and a fairly steep gradient. When the water becomes cooled below the freezing-point large quantities of frazil ice are produced in the riffles and all other turbulent reaches. In time the flowing water becomes fairly viscous with its suspended load of ice-crystals. This causes a reduction in velocity with a corresponding increase in stage.

If the banks are high enough the flow soon becomes tranquil and surface-ice, incorporating all the frazil ice flowing near the surface, forms very suddenly, often with noises resembling thunder-claps.

If the banks are too low to permit the river-stage to rise to the tranquil condition where surface-ice will form, the banks are overflowed. The river then acts like a stream surcharged with silt. The river flows to the low spots filling them with ice. As it flows slush-ice is deposited wherever velocities are slackened along the edges. In this way the stream builds up a new bed and banks with ice until they in turn are overtopped and the river finds a new channel. This process is repeated many times until, if the cold spell continues, the entire valley-floor may be covered with several feet of ice interlaced with a multitude of braided channels.

There is another factor that contributes to rapid ice-formation and the diversion of the stream from one place to another. When the river leaves its natural banks and starts flowing across the valley-floor the water may encounter gravel-beds and rocks that have been cooled to the temperature of the atmosphere, which may be far below freezing. As water touches these beds it is quickly frozen and a condition analogous to anchor-ice immediately obtains, with the consequent elevation of the stream-bed until it is forced into a new location only to repeat the process.

Madison River, Montana, is a stream that exactly fulfills these conditions as it flows through the upper valley of which Ennis is the principal town, and also through the lower valley above the town of Three Forks.

In 1913, the Montana Reservoir and Irrigation Company completed the Hebgen Reservoir. During the summer, this reservoir is operated for the purpose of supplementing the low-water flow of the Madison and Missouri rivers for the benefit of the Prickly Pear Irrigation Project near Helena, and during the fall and winter for eight hydroelectric plants of the Montana Power Company located on those rivers.

The winter of 1916-17 was one of exceptionally sustained, moderately low temperatures, dur-

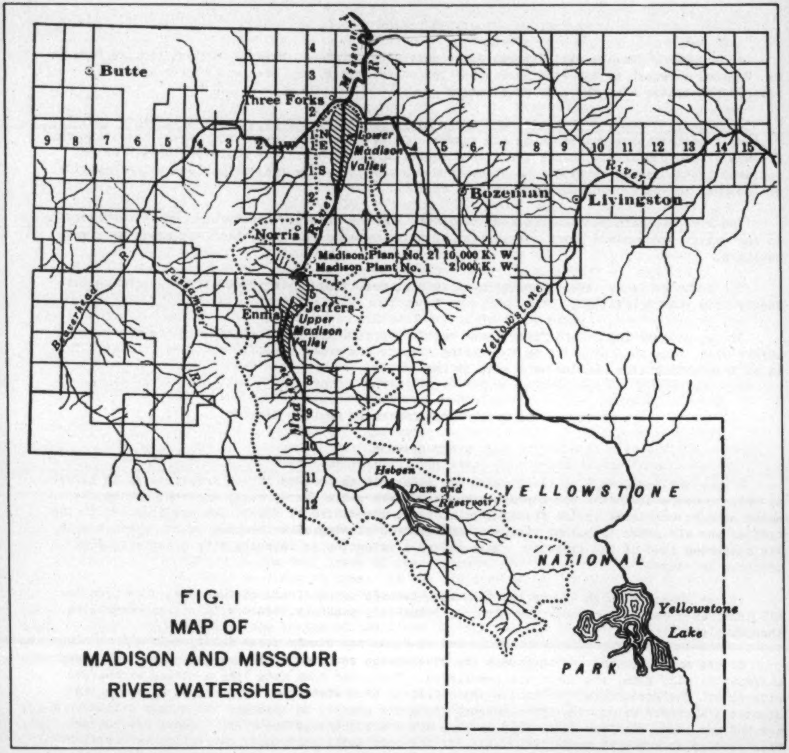

Butte
Three Forks
Missouri R.
4
3
2
1N
1E
1S
2
9
8
7
6
5
4
3
2
1W
4
5
6
7
8
9
10
11
12
13
14
15
Lower Madison Valley
Bozeman
Livingston
River
Yellowstone
Norris
River
Madison Plant No. 2 10,000 K.W.
Madison Plant No. 1 2,000 K.W.
Jeffers
Ennis
Upper Madison Valley
Madison
Beaverhead R.
Passamari R.
5
6
7
8
9
10
11
12
Hebgen Dam and Reservoir
YELLOWSTONE
NATIONAL
PARK
Yellowstone Lake

FIG. I
MAP OF
MADISON AND MISSOURI
RIVER WATERSHEDS

ing which an unusual quantity of frazil and anchor-ice was formed. This resulted in ice-gorges and extensive overflow of the agricultural lands in both valleys. The question arose as to whether the ice-gorging and the overflow were augmented by the operation of the Hebgen Reservoir and of the Madison Reservoir and the power-plants in the canyon between the upper and lower valleys (Fig. 1). Accordingly, there was instituted a thorough study of the ice-gorging and winter-overflow phenomena of Madison River, both from a physical and an historical standpoint, as well as the effect of the operation of the reservoirs and power-plants thereon. This was done in order to ascertain whether such operation was responsible wholly or in part for the overflow and to outline, if possible, some remedial measures.

Two types of ice-gorges were recognized on Madison River, namely, that designated as the "bridging gorge," in which little or no overflow occurs, and that called the "overflow-gorge."

The "bridging gorge" is caused by sudden and sustained extreme low temperatures, say, from -15° to -30° F. This condition causes the maximum quantity of frazil ice to form, and the river is suddenly converted from a turbulent stream to a sluggish flowing mixture throughout its entire length. The river rises and is frozen over for long stretches of its length, thus preventing in these stretches the further formation of frazil- and anchor-ice. As long as the low temperature continues, the water flows beneath the ice-bridge without overflowing its banks appreciably. Figure 2 shows such an ice-bridge with the water flowing beneath it.

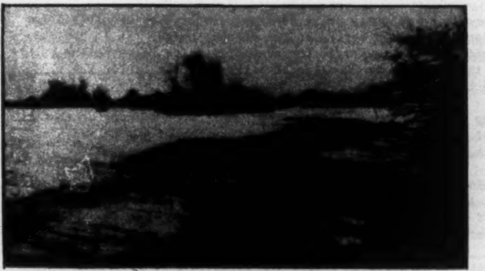


Fig. 2--Typical gorge of the "bridging" type

Fig. 3--Appearance of river after ice-gorge has broken and water has returned to its channel

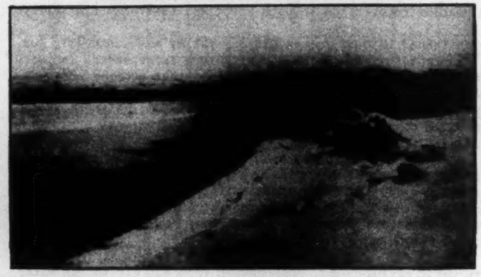


Fig. 4--Frazil-ice floating in river-channel

The "overflow-gorge" is caused by sustained moderate temperatures, say, between 10° and 25° F. Such a condition leaves the river open practically throughout its entire length, causes considerable frazil- and anchor-ice, but not enough to form a "bridging gorge." Therefore, the formation of ice continues unabated, and the many channeled lower part of the valley becomes the gathering ground for all the frazil-, surface-, and anchor-ice formed in the river above.

Between these two distinct types of ice-gorges there is every possible intermediate type, the one merging into the other, causing varying degrees of overflow. The river is thus known to overflow one place one time, and some other place another time, in fact, every possibility of gorging and overflow between the two extremes is known to have occurred. So capricious are these overflows that, during the winter, stock is never allowed to pasture in the bottom-lands. In the history of these valleys, thousands of head of cattle have been trapped and lost in the winter overflow.

By interviewing the old settlers of the valleys, it was found that ice-gorges and overflows were to a greater or less extent of annual occurrence. Winters that stand out especially in this respect are those of 1867, 1875, 1883, 1898, 1910, and 1917.

In the Lower Madison Valley in the decade, 1890-1900, iceboats were successfully used by a colony of sport-loving Englishmen. The ice overtopped the fence posts, giving clear stretches 10 miles or more in extent. In fact, it appears that the limits of the 1916-17 overflow had at times been equalled if not exceeded.

Effect of reservoir-operation

Apart from an increase in winter flow, the effect of a reservoir in such a stream is first to diminish the quantity of ice below it. For example, consider a turbulent river, 100 miles in length, with a valley at the lower end. In its natural condition the river pours into this valley all the ice formed throughout its length.

Now, if a substantial reservoir is built 25 miles above the valley, it will constitute an ice-barrier for the 75 miles of river above it, since no frazil ice can pass the reservoir.

Moreover, the water from this reservoir is slightly above freezing temperature and frazil ice cannot form until the water has been cooled to freezing in the channel below. It is obvious, therefore, that after the construction of the reservoir the quantity of ice reaching the valley will be limited to that formed in the lower 15 or 20 miles of river, whereas, prior thereto, 100 miles of river contributed its ice to the valley.

The first effect of increasing the flow is to diminish the quantity of anchor-ice that may form, due to the increased depth of water reducing the quantity of heat that may be radiated directly from the bed of the stream.

The second effect is to diminish the turbulency and encourage the tendency of the water, at freezing temperature, to remain on the surface. Thus, the formation of frazil ice is more likely to be confined to the surface of the moving water, which is not the case when the water is brought to a uniform freezing temperature by thorough mixing.

The third effect is to increase the quantity of frazil ice about in proportion to the increase in the area of the water-surface.

The fourth effect is to increase greatly the transporting power of the current, thus enabling the river better to carry its icy load without gorging and, therefore, delay the formation of the gorge until a rise of temperature destroys the tendency of the ice to gorge. The increased flow tends to cut out the gorge quicker with a slight rise in temperature; in other words, the river becomes more sensitive to the temperature-changes and the duration of the overflow is less than with the normal flow.

The effect of the Hebgen Reservoir, therefore, aside from the question of increased flow, has been to diminish the quantity of ice reaching the Upper Madison Valley. For the same reasons, the Madison Reservoir which is at the head of the canyon between the two valleys (Fig. 1), has the effect of still further diminishing the quantity of ice in the Lower Valley by eliminating about 80 miles additional of ice-producing river-channel. Hence, before the construction of either reservoir, the Lower Valley was the gathering ground for the ice produced in 150 miles of river. By the construction of the reservoir, the length of ice-producing channel has been reduced to about 25 miles.

Ice-forming factor

The winter of 1916-17 was one of extensive overflow in both Upper and Lower Madison valleys.

The real cause of the unusual overflow of 1916-17 in the Madison Valley was abnormally sustained, moderately low temperatures. The rapidity with which ice will form is dependent far more on the drop in temperature below freezing than any other factor, provided that drop is not sufficient to form a "bridging gorge" throughout the length of the river and thus prevent the further formation of ice. Clear days and nights, cloudy weather, winds, and snows, all have their effect, but they are of minor importance in comparison with the temperature-gradient.

The quantity of ice formed will depend on the amount of heat lost from the water. The heat lost after water has been cooled to 32° F and ice has begun to form is the latent heat of fusion. Virtually, one pound of water is frozen for every 144 Btu extracted from the water. Practically, the same amount of heat is lost in one day with a drop in temperature of 10° as is lost in two days with a drop of 5°; hence, the number of degree-days below freezing in any period will be the measure of the quantity of ice formed during that period.

When the air-temperature is above the freezing-point, heat passes from the air to the water, and latent heat is absorbed by the water with a reduction in the proportion of ice. The quantity of ice thus lost is also measurable by the degree-days above freezing. Hence, in any period, the net quantity of ice is measured by the excess of degree-days below freezing over those above that temperature. These relations, of course, only hold as long as the river remains open and a mixture of ice and water may be considered.

The mean daily temperatures for the months of November to March for each winter were plotted. The winter season was considered to begin on the first date in the fall that the mean daily temperature fell below freezing and to end with the date it rose above freezing in the spring. The areas of these temperature-curves below freezing in excess of those above freezing were found by means of a planimeter. These areas gave for each winter season the number of degree-days below freezing in excess of those above freezing. This quantity was called the ice-forming factor for that season. Figures 5 and 6 show the temperature-curves for the winters of 1871-72 and 1916-17, respectively. Figure 7 shows the ice-forming factors for each of the 53 years of record, arranged in chronological order, and Figure 8, the same factors arranged in order of magnitude. With the exception of the winter of 1871-72, it is seen that the winter of 1916-17 shows the greatest ice-forming factor during the entire 53 years.

The ice-forming factor alone is no measure of the overflow, but merely indicates the net quantity of ice-forming influence from temperatures that obtained during the winter. Overflow results from the type of gorge produced, and one must look to the daily temperature-curves themselves in order to judge the nature of the gorges that would be formed. A comparison between Figures 5 and 6 shows at a glance why the gorge produced during the winter of 1916-17 was of the overflow type, while that of 1871-72 was more likely to have been a "bridging gorge" which did not produce any unusual overflow.

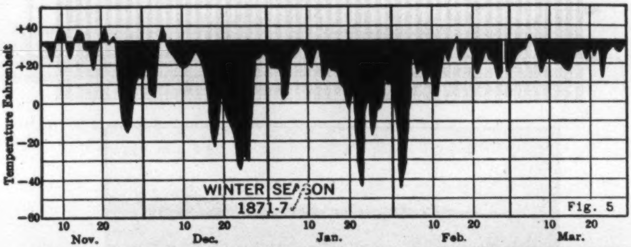


Fig. 5

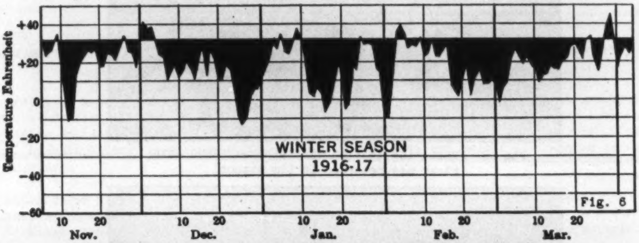


Fig. 6

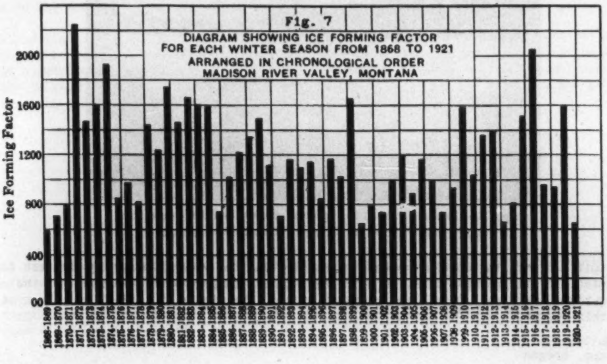


Fig. 7

DIAGRAM SHOWING ICE FORMING FACTOR
FOR EACH WINTER SEASON FROM 1868 TO 1921
ARRANGED IN CHRONOLOGICAL ORDER
MADISON RIVER VALLEY, MONTANA

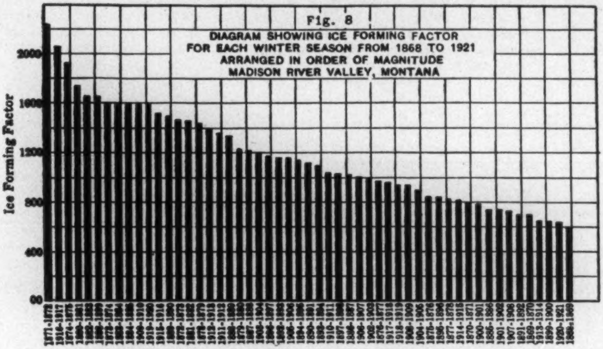


Fig. 9--Frazil-ice left on agricultural lands after river has returned to its channel

Fig. 10--Broken ice-line on bank shows height to which water was raised at time of forming of gorge

From this analysis the conclusion was inevitable that the year showing the greatest ice-forming factor and, at the same time, in which the highest temperatures obtained, was the one producing maximum overflow. Of all the years of record, the winter of 1916-17 was the most abnormal in this regard.

Spalding Building,
Portland, Oregon

JOINT DINNER SESSION

H. P. Boardman, presiding

COLOR-FILM ON SNOW-SURVEYING IN THE CENTRAL SIERRA

Walter Herz

The color-film on snow-surveying in the Central Sierra far surpassed its essential value as a scientific record of snow-surveying by presenting the joyousness of the skier and the delicacy of the winter landscape, as when portrayed in oils and pastels.

DISCUSSION

DR. J. BJERKNES of air-mass fame, who was a guest at the dinner, recounted his experience with Amundsen on the latter's first flight towards the North Pole where each comrade thrilled for the venture and reckoned not the outcome. Daring with reasonableness seemed to him to be the appropriate motto of the explorer.

FORECAST ACCURACY OF WATER-SUPPLY AS MADE FROM SNOW-SURVEYS

R. A. Work, Chairman

STANDARDS AND TERMINOLOGY

R. A. Work

(This matter is in the form of suggestions with questionnaire and correspondence relating thereto.)

In preparing material on accuracy of water-supply forecasts for Oregon for the Snow-Survey Conference at Seattle, Mr. Ryan and the author find that results of many of our forecasts cannot be numerically evaluated. Some designation such as "excellent", "good", "fair", "poor", "very poor", or "unsatisfactory" seems necessary to describe the obtained result as compared to the earlier forecast.

In other cases of course we forecast in terms of acre-feet or flow-units for definite periods and accuracy of such forecasts can be expressed on a percentage-error basis. But, in order to get all forecast-results onto a comparative base, it seems necessary to assign a percentage-error value to the words above.

We realize that a percentage-error of ten per cent in one case may for all practical purposes be considered good forecasting. In other cases, ten per cent error might not be so good. However, not attempting to establish any differential accuracy weighting for various forecasts, we would like to know if the following arbitrary percentages of error can be safely and generally assigned to the descriptive terms we are using:

Percentage by which obtained flow differs from forecasted flow	Word to be used in describing forecast
5	Excellent
5 to 10	Good
10 to 20	Fair
20 to 30	Poor
More than 30	Very poor

By this classification, forecasts less than 80 per cent correct would be classed as poor or worse, and forecasts must be 90 per cent correct or better to be called "good."

Such suggestions as you can give and the thoughts of other snow-survey leaders on the above classification would be appreciated.

W. W. McLAUGHLIN (Chief, Division of Irrigation, Soil Conservation Service, Berkeley, California)--Referring to the Table, I am inclined, where the per cent of departure of the streamflow from our forecast is in excess of 25 per cent, to call it very poor, and certainly where it is more than 30 per cent to indicate it as questionable.

The difficulties which we face in forecasting are appreciated, but we must find some way, as time goes on, to have all of our forecasts within 20 per cent departure.

HAROLD CONKLING (Deputy State Engineer, California Cooperative Snow-Surveys, Sacramento, California)--The terminology of Mr. Work corresponds closely with the ideas held by this Office, and we see no reason why such a classification should not be adopted.

JAMES C. MARR (Irrigation Engineer, Soil Conservation Service, Boise, Idaho)--(1) As a means of interpreting the relative value of the forecasts in terms of requirements, use of the words "excellent", "good", "fair", etc., appears worth while; however, ten per cent accuracy might be "good" (serviceable or of high value to the water-user) in one case and not so good in another.

(2) If it is merely the intent to show how near to accurate a forecast turns out to be and it is possible to arrive at the percentage-difference, as is implied by definition of terms, then why not use the percentage-differences instead of the terms?

(3) If the use of terms rather than percentage-differences are intended to avoid embarrassing exactness, then the definition of terms might be too precise for the purpose.

(4) Quite often the best forecast possible to make is spread between two significant figures. One of these might be within five per cent accurate and the other ten per cent, yet the forecast might actually be excellent considering the purpose served.

Perhaps it might be worth while to recite the case of the forecast for Boise River last year. William Tuller, the Project Manager of Boise Project, forecasted the Boise River runoff at 1,400,000 to 1,500,000 acre-feet. It actually amounted to 1,364,000 acre-feet. About 100,000 acre-feet ran to waste. An available supply of 1,400,000 acre-feet was needed to fill all water-rights. What may be the utility of this forecast or of its accuracy?

O. W. MONSON (Irrigation Engineer, Agricultural Experiment Station, Montana State College, Bozeman, Montana)--The method suggested, that of rating forecasts as "excellent", "good", "fair", "poor", or "very poor" according to the percentage of error, appears to me to be practical; and I think it would be well if this could be standardized so that each word would rate definitely, referring to a definite degree of accuracy.

I think there would be no argument about the "excellent", but there may be a tendency to call a forecast "good" which really should be rated as "poor" when the actual percentage of error is considered. However, I agree that conditions will affect the value of forecasts. There will be cases where a forecast which might be 20 per cent in error would be considered a "good" forecast for that particular watershed. This need not affect the standard, however, as it would take only a short time for all concerned to recognize that for a particular watershed only a "fair" forecast may be expected.

CARL ELGES (Assistant Meteorologist, Nevada Agricultural Experiment Station, Reno, Nevada)--Regarding forecast-accuracy of water-supply as made from snow-surveys, I had hoped to discuss or take part in a discussion of this matter at the Seattle Meeting.

I am not familiar with forecasts which "cannot be numerically evaluated" but it seems to me that if such is the case it will also be difficult to give them a word-classification, and am glad now to be present, for apparently a calculation is necessary to determine under which group the accuracy will be entered. For a number of years Dr. Church made some forecasts of runoff in general terms based entirely upon snow-surveys. Since many factors must be considered and since we know that the same amount of snow may give different amounts of runoff, I believe it very essential that quantitative forecasts be made. This has brought on the added burden of obtaining stream-flow records where desired and not taken by other agencies so that the runoff can be evaluated and correlated with the snow-cover.

If an attempt is made to arrive at a uniform method of expressing the forecast accuracy, it might be well to consider and discuss the following: Percentage-deviation of the forecast from the actual; percentage of deviation of the actual from the forecast; and the percentage-deviation between the forecast and actual--all figures being expressed in terms of normal. The last method is the one used here in Nevada. The forecast of runoff for the period March to July for the Humboldt River at Palisade for 1934 will perhaps demonstrate the advantages of this system. The normal for that period at the station is 255,000 acre-feet. The forecasted probable flow was ten per cent of normal based upon a 60 per cent snow-cover and other existing factors. The actual flow received was 9,938 acre-feet or about 3.7 per cent of normal. Everyone who has anything to do with the water-distribution or use agrees that this is an excellent forecast. Expressed in terms of percentage of normal the forecast deviated from the actual only 6.3 per cent. However, if expressed in terms of the percentage-deviation of forecast from actual, the forecast was 170 per cent off, thus misrepresenting the true value of the forecast.

To further illustrate the differences of the three methods mentioned in the foregoing paragraph, Table 1 was prepared giving actual results of three years for the Truckee River at Farad.

Table 1

Item	Acre-feet	Per cent of		
		Normal	Actual	Forecast
Low years				
1934, Forecast	70,000	21.5	94.3	100
Actual	74,270	22.8	100	106
Deviation	4,270	1.3	5.7	6
1939, Forecast	110,000	33.8	126.5	100
Actual	86,980	26.7	100	79
Deviation	23,020	7.1	26.5	21
High year				
1938, Forecast	480,000	147.4	82	100
Actual	586,000	179.9	100	122
Deviation	106,000	32.5	18	22

By inspection of Table 1 it can be seen that for supernormal years the percentage-of-normal method will give a greater deviation than the others but for the low years it has the advantage.

To use the percentage-of-normal method of expressing the forecasts it is not necessary to make lengthy computations if one does not desire to do so. For the Humboldt River the 255,000 acre-feet normal given in this letter was arrived at by studying over the record from 1904 to 1928. It has not been altered since. Recent years would have reduced the normal considerably but this is undesirable for the reason that it takes about a 255,000 acre-feet runoff to satisfy or give a 100 per cent water-supply to the irrigated lands of the Basin. It seems that the water-users have accepted that figure as normal and when told that there will be a 60 per cent supply they immediately interpret it to mean that about 60 per cent of the land having the oldest rights will be served water.

Regional Reports for the Northern Watersheds

(1) ACCURACY OF OREGON WATER-SUPPLY FORECASTS, 1936-1939

R. A. Work and J. H. Ryan

It seems fitting at this Western Interstate Snow-Survey Conference that candid inventory be taken of progress in the water-supply-forecasting field. It has been well said that proof of the pudding is in the eating; so review of obtained stream-flows when compared with the forecasted amounts provides a yardstick of performance.

Going back to 1935, the year in which the United States Department of Agriculture began cooperation with the Oregon State Engineer, the Oregon Agricultural Experiment Station, and other agencies in the snow-survey work, our total resources, both as to personnel and funds, were limited. The task ahead appeared then to include three principal spheres of activity:

(1) The actual locating, clearing, marking, and maintenance of courses on numerous stream-basins; the providing of equipment and shelter-facilities; the selection and training of additional field-personnel; and the actual securing of field snow-measurements according to predetermined schedules.

(2) The transmission of results from the field to a central office.

(3) The assembly of information in the central office, redistribution to other cooperating agencies, analysis of results, and preparation and release of forecasts.

The decision was reached to direct immediate energies and resources into the first- and second-activity spheres, for without field-data there could be no forecasts. Accordingly, needed snow-courses were added gradually, until the Oregon network increased from a skeletal 20 measured in 1935 by State Engineer watermasters to 90 courses permanently established by late 1939. Similarly, rapid communication methods between even the most isolated snow-surveyors and the various centralized offices were concurrently established and maintained. This included the establishment of a short-wave radio system. Much of the limited money available went, these first few years, into the purchase of equipment or construction of urgently needed shelter-cabins.

For these reasons, and because adequate records were available on only a few courses, correlation-work necessarily has lagged behind accomplishments in the field. Now, however, with the snow-course network practically complete, with satisfactory methods of communication established, with fewer needs for equipment, and with the most urgent demands for shelter-cabins satisfied, more resources will be available for analysis of incoming results. A barely sufficient record on approximately 70 new snow-courses is just becoming available.

It is true that irrigation-supply or stream-flow forecasts have been issued in Oregon each year since 1936. It should clearly be understood, however, that the annual forecasts, or estimates as they might better be called, while in all cases based on snow-measurements and related data, in only a few cases resulted from definite correlations. The following paragraph taken from the Foreword to the Oregon 1940 Irrigation Water-Supply Forecast, issued on April 11, emphasizes this point:

> "For the reason that a great many of the Oregon courses are but newly established, and in view of the further fact that on very few of the courses do the records extend back for more than a few years, it has been difficult to arrive at definite correlations between water on the ground as snow and subsequent stream-flow. In the case of certain stream-basins, however, correlations have been made. Full use has been made of correlations developed by engineers of cooperating agencies.
>
> "Lacking the extended records on which accurate forecasts must be based, but believing that information accumulated to date is of value in forming general estimates of prospective water-supplies for Oregon in 1940, a series of water-forecast committee meetings was held in important irrigated regions of Oregon for the fifth consecutive year during the period April 5 to 12. An informal report was prepared of the results of each meeting, outlining the irrigation water-supply prospects as of April 1 for various Oregon stream-basins. The gist of these reports is reproduced herewith. It is understood, of course, that later modifications of the forecasts may be required in accordance with unforeseen deviations of precipitation and temperature from normal during the runoff-season."

In preparing data for the present report, it was found that results of many of the forecasts could not be evaluated numerically. Some designation such as "excellent", "good", "fair", or "poor" seemed necessary to describe the obtained result as compared to the forecast. Two forecasts issued in 1939 will illustrate this point:

On April 5, the following forecast was issued for a certain central Oregon area: "Sufficient water-supplies are in sight for the Squaw Creek Irrigation District." Due to record-breaking spring drought, the water-supply for that District became somewhat short after July 15. Therefore, that forecast was classed as "poor". On April 5 the following forecast was issued for another irrigated district in central Oregon: "The Plainview and McAllister ditches are expected to be shut off earlier than usual and may not receive water after about July 1." Those ditches were forced to shut off on July 5 because of water-shortage. That forecast was called "good"

In three-fourths of the cases, forecasts were in terms of acre-feet or flow-units for definite periods. Accuracy of such forecasts could be and is expressed on a percentage-error basis. But, in order to place all forecast-results on a comparative base, it seems necessary to assign a percentage-error value to the descriptive words "excellent", "good", "fair", and "poor"

It is realized that a percentage-error of ten per cent in some cases might not be considered especially good forecasting. In other cases, such an error would not only be allowable, but would represent very practical and excellent forecasting. However, for purposes of comparing general forecast-accuracy from year to year, differential ratings for various stream-basins probably should not be used. Assignment of the following arbitrary percentages of error to the various descriptive terms used were made to describe forecast-accuracy:

Table 1--Accuracy of Oregon water-supply forecasts, 1936-39

Source forecasts	Forecast, accuracy	Year				Total period
		1936	1937	1938	1939	
All	Excellent	7	10	21	15	53
	Per cent of annual total	22.6	23.3	48.8	24.2	29.6
	Good	10	13	8	15	46
	Per cent of annual total	32.2	30.2	18.6	24.2	25.7
	Fair	7	8	7	12	34
	Per cent of annual total	23.6	18.6	16.3	19.4	19.0
	Poor	7	12	7	20	46
	Per cent of annual total	22.6	27.9	16.3	32.2	25.7
	Total	31	43	43	62	179
	Per cent "Good" or better	54.8	53.5	67.4	48.4	55.3
	Per cent "Fair" or better	77.4	72.1	83.7	67.8	74.3
Based on Committee estimates	Excellent	6	9	14	11	40
	Per cent of annual total	26.1	28.1	53.9	22.5	30.8
	Good	7	7	5	15	34
	Per cent of annual total	30.4	21.9	19.2	30.6	26.2
	Fair	6	6	5	8	25
	Per cent of annual total	26.1	18.8	19.2	16.3	19.2
	Poor	4	10	2	15	31
	Per cent of annual total	17.4	31.2	7.7	30.6	23.8
	Total	23	32	26	49	130
	Per cent "Good" or better	56.5	49.0	73.1	53.1	57.0
	Per cent "Fair" or better	82.6	67.8	92.3	69.4	76.2
Based on correlations	Excellent	1	1	7	4	13
	Per cent of annual total	12.5	9.1	41.2	30.8	26.5
	Good	3	6	3	0	12
	Per cent of annual total	37.5	54.5	17.6	0.0	24.5
	Fair	1	2	2	4	9
	Per cent of annual total	12.5	18.2	11.8	30.8	18.4
	Poor	3	2	5	5	15
	Per cent of annual total	37.5	18.2	29.4	38.4	30.6
	Total	8	11	17	13	49
	Per cent "Good" or better	50.0	63.6	58.8	30.8	51.0
	Per cent "Fair" or better	62.5	81.8	70.6	61.6	69.4

Percentage by which obtained flow differs from forecasted flow	Adjectives used in describing forecasts
5	Excellent
5 to 10	Good
10 to 20	Fair
More than 20	Poor

By this classification, forecasts less than 80 per cent correct would be classed as "poor" and only forecasts 90 per cent correct or better would be called "good". Forecasts 95 per cent correct or better are entitled to a classification of "excellent".

As to the actual performance-record of the Oregon Water Forecast Committees, 179 water-supply estimates of one sort or another were issued in the four years 1936-39. Of these, 30 per cent were "excellent", 55 per cent were "good" or better, and 75 per cent were "fair" or better.

In 1936, 55 per cent were "good" or better; in 1937, 54 per cent were "good" or better; in 1938, 67 per cent were "good" or better--the accuracy seemed to be improving--but in 1939, only 48 per cent were "good" or better. Examination of the inaccurate forecasts for 1939 showed that in 78 per cent of the cases inaccuracy was due to sharp reduction in obtained flows from forecasted amount. That this reduction resulted from the greatest spring drought ever recorded in Oregon since weather-records began in 1880 seems evident. Furthermore, during this dry period, temperature was generally above normal and some new high-temperature records for the time of year were established near the close of the period. Had it not been for this unprecedented spring drought, it is believed that the improvement in the forecasting record would have continued and 75 per cent of the forecasts would have been "good" or better in 1939.

Of the 179 forecasts issued 49, or approximately 27 per cent, were based either on definite correlation-curves, or at least on years of very intensive study by one or more engineers of cooperating agencies. As a matter of interest, the accuracies of these 49 forecasts were compared with those of the remaining 130 estimates arrived at in group-meetings. Surprisingly, the results showed the group-estimates to be slightly more accurate through the four-year period than were the forecasts based on carefully determined correlations. Over the four-year period, 57 per cent of the estimates of the Committee were 90 per cent accurate or better, as compared to 51 per cent of the forecasts based on correlations.

Although the Forecast Committee estimates compare favorably with forecasts derived from correlation-curves, it seems that this apparent contradiction of logic can be explained by the fact that most of the correlation-work to date has been with streams that are very hard to forecast accurately because of their ready response to slight climatic abnormalities during the runoff-season April to September.

U. S. Soil Conservation Service (R.A.W.),
Medford, Oregon
Office of the Oregon State Engineer (J.H.R.),
Salem, Oregon

(2) ACCURACY OF STREAM-FORECASTS ON THE BOISE RIVER, IDAHO, 1939

James C. Marr

My letter to R. A. Work [p. 980] represents the forecast-accuracy for 1939 on the Boise River, for which the longest snow-survey record is available.

Since it is brief, it will be requoted here:

> "William Tuller, the Project Manager of Boise Project, forecasted the Boise River runoff at 1,400,000 to 1,500,000 acre-feet. It actually amounted to 1,364,000 acre-feet. About 100,000 acre-feet ran to waste. An available supply of 1,400,000 acre-feet was needed to fill all water-rights."

U. S. Soil Conservation Service,
Boise, Idaho

(3) FORECAST AND RUNOFF, LAKES COEUR D'ALENE AND CHELAN, 1939

Walter E. Johnson

The comparison of forecasts and runoffs for lakes Coeur d'Alene and Chelan in 1939 are shown by Figure 1. Both forecasts are in the upper brackets of accuracy [see p. 985].

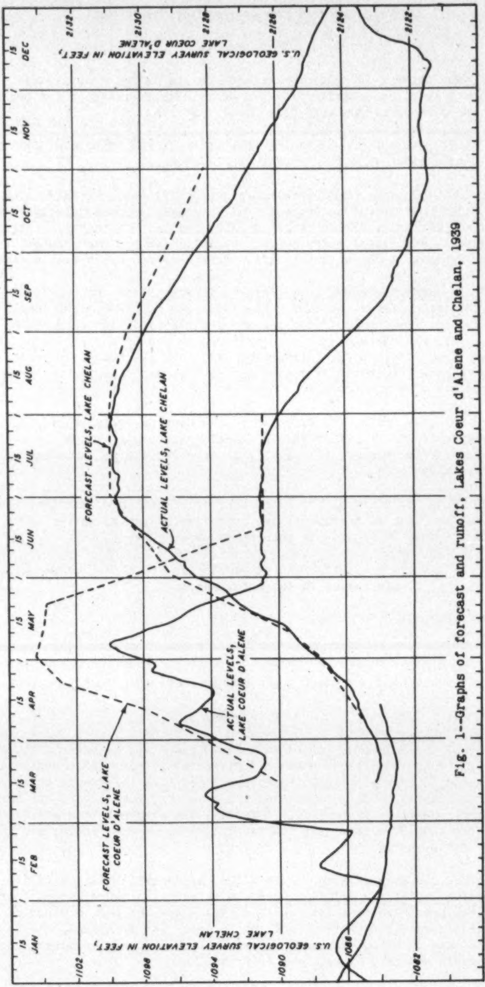


Fig. 1--Graphs of forecast and runoff, Lakes Coeur d'Alene and Chelan, 1939

Washington Water Power Company,
Spokane, Washington

(4) ACCURACY OF STREAM-FORECASTS IN MONTANA

O. W. Monson

The earliest snow-surveys in Montana were made on the Swiftcurrent Watershed by the United States Geological Survey in cooperation with the Water Rights Branch of the Department of Lands, Canada, in 1922, and have been made each year since that time.

Snow-survey studies were begun by the Montana Agricultural Experiment Station in 1934 and have gradually expanded since then to a network of 32 courses.

The United States Geological Survey snow-surveys provide a basis for estimating the water-supply available for the Milk River Irrigation Project. The forecasts are made jointly by the United States Geological Survey and the Water Rights Branch of the Canadian Government. These forecasts have been rather consistent, and except where summer precipitation has been unusual the forecasts have been reasonably close to the actual runoff. Agreement has often been within five per cent.

The United States Army Engineers have prepared forecasts for the runoff of the Missouri River above Fort Peck each year since 1935. The forecasts for 1935, 1936, and 1937 were quite close, being within eight per cent. The forecasts for 1938 and 1939 were off 29 and 40 per cent, respectively. These discrepancies were ascribed to unexpected variation in summer precipitation. Summer precipitation is an important factor in the runoff of April 1 to July 31, since three times as much precipitation occurs during the runoff-period as during the snow accumulation-period.

Up to the present time, forecasts released by the Montana Agricultural Experiment Station have been on a comparative basis rather than a quantitative basis. This has been justified because of (1) short period of record, (2) lack of storage-facilities, thus making quantitative estimates of little value.

Each year the forecast, based on the water-content of the snow, has been compared with that of the previous year and also with those of the past five years or the period of record. Such forecasts have considerable value and are reasonably dependable.

Snow-survey data now cover a sufficient period to justify more precise methods which, if successful, should be of greater value to the water-users.

Montana Agricultural Experiment Station,
Bozeman, Montana

(5) UPPER MISSOURI RIVER FORECASTS AT FORT PECK, 1938 AND 1939

D. B. Freeman

On April 1, 1938, the snow-pack in the Fort Peck Headwaters Area was 116 per cent of normal. However, in view of the dry conditions which had persisted through 1937, and in anticipation of a continued deficiency in precipitation, it was predicted that the runoff above Fort Peck during the four-month period, April to July 1938, would be only approximately 50 per cent of normal. This forecast was not subsequently revised. Actually, the precipitation which occurred, was above normal (130 per cent of normal) for the first time in several years, and the resulting runoff was 89 per cent of normal.

On April 1, 1939, the snow-pack in the Fort Peck Headwaters Area was 86 per cent of normal, and, on the assumption that the precipitation would be normal or above normal during the period April to July, it was predicted that the runoff during this same period would be approximately normal The precipitation during April, 1939, was 61 per cent of normal, and by May 1, 1939, the water-content of the snow had decreased to only 40 per cent of the water-content on April 1. The runoff during April was only 82 per cent of normal.

In view of these circumstances, it was decided to revise the prediction of April 1. Accordingly, it was predicted that in the event the total precipitation during the four-month period April to July, 1939, proved to be below normal, the corresponding runoff would not exceed 80 per cent of normal. The actual total precipitation during the four-month period April to July, 1939, was only 88 per cent of normal, and the corresponding runoff was only 60 per cent of normal.

These comparatively large errors in the predictions for the two years may be attributed largely to the effects of rainfall during the period for which the predictions of runoff were made. A study of the effect of rainfall on runoff during the period for which predictions have been made resulted in the use of a revised procedure in predicting the spring runoff in 1940.

U. S. Engineer Office,
Kansas City, Missouri

(6) ACCURACY OF FORECASTS IN BRITISH COLUMBIA IN 1939

R. C. Farrow

In a general way runoff in British Columbia followed the trend indicated by snow-cover measurements, as outlined in my "Report on British Columbia snow-surveys and runoff-probabilities" of April 6, 1939. The above-normal snow water-content reported for the Coastal Belt was reflected in runoff above normal. In the Kootenay and Columbia River basins, as mentioned in the above report, snow water-content varied considerably but averaged about normal; runoff, however, was fairly consistently below normal at about 90 per cent.

Data subsequent to the above-mentioned report caused a downward revision of some forecasts. Where the changes were material, the interested authorities were notified accordingly.

Table 1 gives a summary of the forecasts made, the accuracy, attained, and comments on possible causes of discrepancies.

Table 1

Area	Stream		No. of courses involved	Runoff April to August		Error, per cent of actual
	Name	At		Forecast	Actual	
				acre-feet	acre-feet	
Coastal	Stave River	Stave Falls	3	1,339,000	1,180,000	+13.5
	Powell River	Powell Lake	2	830,100	1,140,500	-27.2
Kootenay	Lardeau	Gerrard	1	430,400	492,000	-12.5
	Duncan	Howser	1	1,503,000	1,743,000	-13.8
	Elk	Elko	2	1,077,000	912,000	+18.1
	Slocan	Crescent	1	1,682,000	1,623,000	+ 3.6
	Kootenay	Wardner	3	3,578,000	3,405,000	+ 5.1
	Kootenay	Glade	5	14,825,000	14,160,000	+ 4.7
Okanagan	Okanagan	Penticton	5	379,800	225,700	+68.3
Columbia	Columbia	Golden	3	2,016,000	1,951,000	+ 3.3
	Columbia	Revelstoke	6	16,832,000	16,828,000	+ 0.1
	Columbia	Trail	14	35,884,000	34,680,000	+ 3.4

Forecasting for Coastal streams presents many more difficulties than for those in the interior; the extreme ruggedness and heavy growth of the Coast Range makes it very difficult to locate snow-courses where wanted. Over large areas most of the winter precipitation falls as rain, which changes gradually to snow at the higher levels; the snow-covered area changes from year to year, but not in proportion to snow-depth recorded at the snow-courses. Precipitation during runoff is a big factor, and unfortunately the precipitation-stations are located on the lower, and settled, reaches of the basins, and therefore give little or no indication of conditions upstream and at higher altitudes.

Stave River predictions are improving in accuracy with time and experience. This is the first year of forecast for Powell River. Precipitation during runoff appears to have increased the runoff above that forecast.

Kootenay-Columbia basins--As mentioned in my report of April 6, excessively high temperatures commenced about the middle of March, and took a heavy toll of snow prior to the end-of-March snow-sampling. This condition was general throughout most of the interior of the Province, and in the Kootenay and Columbia basins represented a typical chinook (Foehn) condition, in which the visible snow-shrinkage was not accompanied by any marked increase in runoff, and therefore represented an evaporative loss.

I rather feared that the notable shrinkage which had occurred prior to sampling on many snow-courses might cause serious errors in forecasting. On some tributary streams this was the case, but for the main Kootenay and Columbia forecasts the distribution of snow-courses, both in area and in altitude, was evidently sufficient to more or less reflect the runoff-potential, since all these forecasts were within reasonable limits of accuracy.

It will be noted, however, that with the exception of the Lardeau and Duncan rivers, all the Kootenay and Columbia forecasts were too high (as indicated by their "plus" errors). I attribute this uniformity of error to the fact that the high prevailing temperatures in March would take a heavier toll of the snow at low than at high elevations. In fact, the ground was bare by the end of March at elevations where snow is normally found a month later. This would reduce the total area of snow-fields and moreover reduce the total potential runoff from those areas below the snow-courses to a greater degree than from the areas above the courses and, in thus upsetting the normal balance, cause the average expectation of runoff as indicated by snow water-content to exceed actual runoff.

The Lardeau and Duncan basins are usually less affected by chinooks than other parts of this area, and showed far less indications of early melting. They lie in a local wet belt, and above-normal rains in April and May probably account for the excess of actual runoff over forecast.

Okanagan Basin--A study of precipitation- and runoff-data indicated from the first that the fundamental relationship between snow-cover and runoff might very often be obscured by distorting factors.

Early spring and summer rains are usual and, falling on the still snow-covered areas, they no doubt have a marked effect in sustaining runoff. The area is semi-arid, the summers are hot and dry, often with considerable wind, and if the hot weather comes early in place of the usual cooler weather and light rains, it is quite evident that the evaporation-loss from the snow-cover may be excessive.

Correction for spring field-moisture-deficiency is now made [see Trans. Amer. Geophys. Union, 1939, pp. 121-124] and application of this correction to two years of snow-survey data and past precipitation-records of snowfall vastly improved their relationship to runoff. This factor appears to be an important one in this Basin.

Unfortunately the available precipitation-records only go back 14 years, 11 years, and 10 years, respectively, at three stations, and during these periods of record there were no years of very marked deficiency in spring precipitation till 1938.

Water Rights Branch,
Victoria, British Columbia

(7) THE ACCURACY OF FORECASTS IN THE PACIFIC NORTHWEST WITH REFERENCE ONLY TO THE BOW AND SAINT MARY RIVER BASINS

W. T. McFarland

In order to determine the probable runoff in a drainage-basin during the critical months of the irrigation-season and so be able to plan how the available supply of water can best be utilized by any irrigation-system, it is necessary to find out what the average water-content of the snow is in the drainage-basin concerned above a certain elevation. For this purpose snow-courses are laid out at selected points and samples taken at practically the same time each year. The location of these courses is shown on the attached Figures 1 and 2. These samples when weighed give the depth of water contained in the snow measured, and the average of all the samples taken gives the average depth of snow and average water-content on each course measured and also gives a close estimate for the whole drainage-area.

It is not the writer's intention to discuss the method used except to state that the percentage- or index-method is believed to be the most suitable for both basins under review and it has been used since 1921. Briefly this method is the obtaining of an index-figure which is the average of the various means determined for the several courses. Both the Bow and Saint Mary rivers rise on the eastern slope of the Rockies in regions of perpetual snow and ice. Below the glaciers are many cirques which usually contain a small lake and are bounded by high precipitous walls which are conducive to severe slide-conditions. These slides fill the valleys many feet

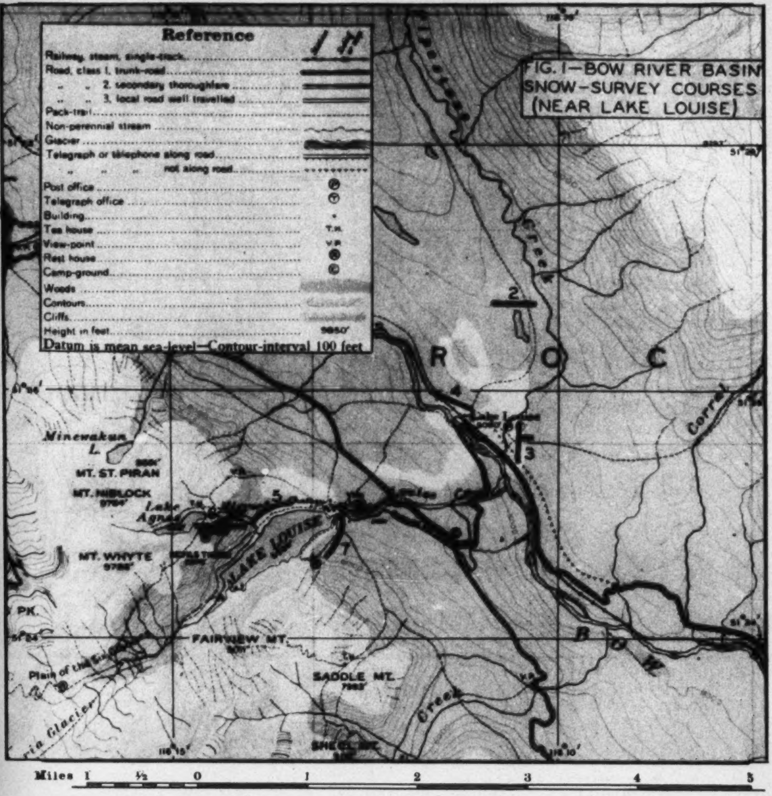

Reference
Railway, steam, single-track
Road, class 1, trunk-road
2. secondary thoroughfare
3. local road well travelled
Pack-trail
Non-perennial stream
Glacier
Telegraph or telephone along road
not along road
Post office
Telegraph office
Building
Tea house
View-point
Rest house
Camp-ground
Woods
Contours
Cliffs
Height in feet
9850'
Datum is mean sea-level—Contour-interval 100 feet
R O C
Creek
Corral
Minewakun L.
MT. ST. PIRAN
MT. NIBLOCK
Lake Agnes
MT. WHYTE
LAKE LOUISE
FAIRVIEW MT.
SADDLE MT.
Plain of the Six Glaciers
Glacier
B O W
Creek
1
2
3
4
5
6
7
116°15'
116°10'
Miles 1 ½ 0 1 2 3 4 5

FIG. 1—BOW RIVER BASIN SNOW-SURVEY COURSES (NEAR LAKE LOUISE)

thick with packed snow. The lakes act as stabilizers and as a result the runoff remains at a relatively high stage for a long duration and eliminates to a certain extent the excessive floods common to many mountainous streams not subject to slide-conditions.

Since a large percentage of both drainage-basins lies between elevations of 5,000 to 8,000 feet, the altitude will govern to a certain extent the retention of snow- and ice-deposits.

These conditions which prevail in both basins and the fact that the snow-courses are so located as to best represent the average snow-conditions within their range, no doubt materially assist in obtaining such a close percentage in our forecasts each year to the actual runoff.

Snow-surveys on the Saint Mary River Basin (Fig. 2) were started in 1922 and have been made at practically the same time each year ever since. It is now feasible to forecast with a reasonable degree of accuracy the runoff during May, June, and July each year. In the fall of 1936 part of the Saint Mary Area was burnt over. It was found necessary to completely abandon one course and to lay out another. Up to the present we have not been able to determine what effect the fire has on our forecast of the probable runoff. I have endeavored to state briefly the characteristics of the watersheds, type of equipment, and method used.

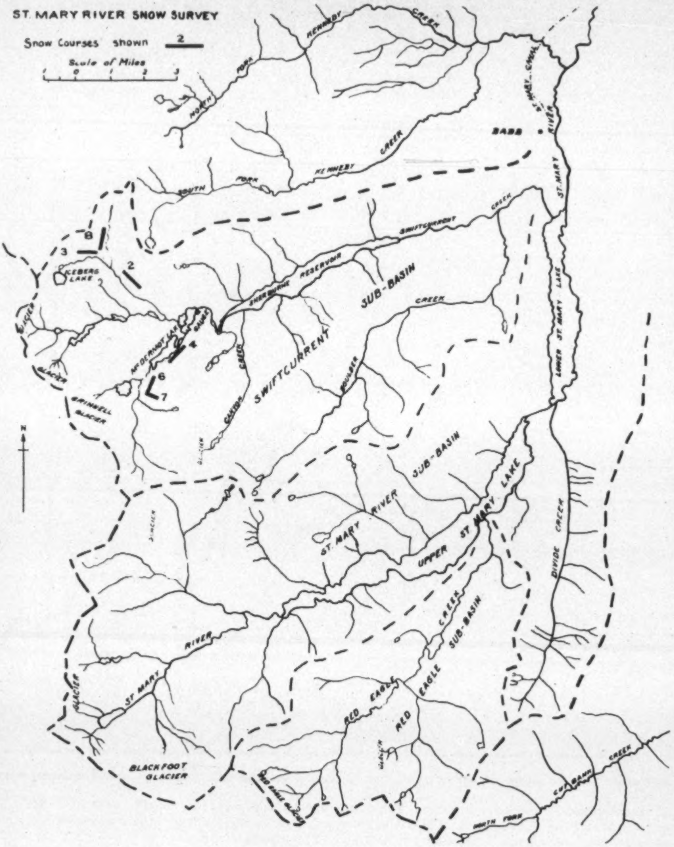

ST. MARY RIVER SNOW SURVEY
Snow Courses shown 2
Scale of Miles
1 0 1 2 3
N
NORTH FORK
KENNEDY CREEK
SOUTH FORK
KENNEDY CREEK
ST. MARY CANAL
ST. MARY RIVER
BABB
8
3
2
ICEBERG LAKE
GLACIER
GLACIER
GRINNELL GLACIER
McDERMOTT LAKE
4
6
7
SHERBURNE RESERVOIR
SWIFTCURRENT CREEK
SWIFTCURRENT SUB-BASIN
CANYON CREEK
GLACIER
BOULDER CREEK
LOWER ST. MARY LAKE
SUB-BASIN
ST. MARY RIVER
UPPER ST MARY LAKE
DIVIDE CREEK
GLACIER
RIVER
ST MARY
GLACIER
BLACKFOOT GLACIER
RED EAGLE GLACIER
RED EAGLE
RED EAGLE CREEK SUB-BASIN
GLACIER
NORTH FORK
CUT BANK CREEK

Fig. 2

In 1939 we forecasted a runoff of 63,880 acre-feet whereas the actual runoff was 57,080 acre-feet, which was 12 per cent less than predicted.

Had we taken into consideration the lowest course shown as S S 2 on the plan, which has been now abandoned owing to the fact that this area has been burnt over, our prediction would have been 100 per cent correct.

The snow-survey of 1940 has recently been completed and we predict the runoff will be 71 per cent of normal.

Snow-surveys on the Bow River (Fig. 2) were started in 1937. Four courses were laid out in the fall of 1936 and three more added in the fall of 1939. It will be necessary to continue these surveys for several years yet before we feel assured that our estimate of the probable runoff in this Area for the months of April, May, June, and July can be made with a fair degree of accuracy.

In 1939, which was the third year of the survey, we predicted a runoff of 587,000 acre-feet against an actual runoff of 556,550 acre-feet, which amounted to 94.8 per cent of our estimate.

The snow-survey of 1940 was completed at the end of March. Our forecast is that the actual runoff will be about 82 per cent of normal.

Up to and including 1939 the standard Mount Rose snow-sampler No. 408 together with the Mount Rose snow-weighing balance was used. This was checked against the new improved Utah aluminum tube and balance. The results were practically the same. The latter equipment which is apparently more up to date was more satisfactory and the samples could be recorded in half the time due to the improved balance. From now on we will use the new equipment.

In addition to actual snow-samples, water-levels of the lakes, stream-discharge, and numerous photographs taken at camera-stations give much additional information.

Table 1--Comparison of forecasts and actual runoff in Swiftcurrent Creek

Year	Water-equivalents	Runoff May to July		Error forecast
		Forecast	Actual	
	inches	acre-feet	acre-feet	per cent
1922	22.8	69,010	75,100	- 8.1
1923	30.9	80,020	70,900	+12.9
1924	22.0	67,920	66,100	+ 2.8
1925	38.9	90,900	89,800	+ 1.2
1926	4.1	43,580	33,900	+28.6[b]
1927	33.2	83,150	83,600	- 0.5[a]
1928	37.4	88,860	91,100	- 2.5
1929	18.1	62,620	56,400	+11.0[b]
1930	10.7	52,550	52,500	0.0
1931	11.1	53,100	53,500	- 0.7
1932	30.6	79,620	70,000	+13.7[b]
1933	37.7	89,270	90,800	- 1.7
1934	24.4	71,180	73,400	- 3.0
1935	29.4	77,980	66,310	+17.6[b]
1936	25.0	72,000	66,410	+ 8.4
1937	25.4	69,640	73,070	- 4.7
1938	30.3	77,480	73,490	+ 5.4
1939	21.8	63,880	57,080	+11.9

[a] Excessive precipitation in certain areas. [b] Precipitation low in certain areas.

It must be remembered that in estimating the water-value of snowfall, superficial appearances and depths only are unreliable and that photographs may actually be deceiving.

Now as to the accuracy of our forecasts, which is most important, covering the period of our snow-surveys, I am showing in Table 1 the percentage of error involved in Swiftcurrent Creek.

In the 17 years under comparison it will be noted that nine were not over five per cent in error; two were between five and ten per cent; four were between ten and 15 per cent; two over 15 per cent; and the average was within six per cent. (Note: 1922 is not included owing to lateness of survey.)

Except for the four years when there was very little precipitation, our forecasts were close. When one considers that no corrections have been applied for years either with low or excessive precipitation, it is remarkable how close our forecast has actually come.

In conclusion, I believe that I can safely state that our runoff-prediction in the Swiftcurrent Area of the Saint Mary River Watershed will now be within ten per cent of the actual runoff during May, June, and July for all years when the rainfall during that period is about normal.

Dominion Water and Power Bureau,
Calgary, Alberta, Canada

[For report of Chairman of Executive Committee of Western Interstate Snow-Survey Conference, personnel of that Committee for 1940-42, and list of members and guests attending the Seattle Meeting, see section "Minutes of Seattle Meeting" on pages 1051-1055.]

ADDENDUM

[The following matter was received too late to be included in its proper place in the volume.]

DIFFICULTIES OF SNOW-SURVEYING

John V. Salo

Figures 1 to 6 are reproductions of photographs showing some of the difficult conditions with which the snow-surveyor is faced at times in the Merrimack Drainage-Area [see pp. 858-870].

The views in Figures 1 to 5 are typical of the terrain in the north and northeast sections of the Area. The aerial tramway (Fig. 1) provides transportation to reach the survey-station on the summit of Cannon Mountain. During 1940, because of work of maintenance, it was necessary to climb by snow-shoe to the summit on two separate occasions by way of the ski-trails. This involves a vertical rise of about 2,200 feet in a distance of one and three-quarter miles. The ascent by snow-shoe takes one and one-half hours and the return about 30 minutes.

A typical view of the wooded sections at lower elevations is shown by Figure 6. It illustrates the type of backwoods dirt-road used to reach ten of the survey-stations. If we reach these roads ahead of the snow-plow, after a snow-storm, we must abandon the automobile and resort to snow-shoes. The troublesome problems appear in the early spring when the dirt-roads are soft; extrication of automobiles from mud and ditches has taught us many tricks.

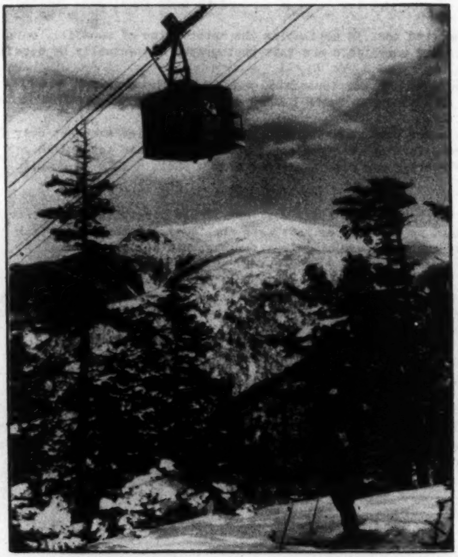


Fig. 1--Cannon Mountain Aerial Tramway with Mount Lafayette in background [c R. E. Peabody--1939]

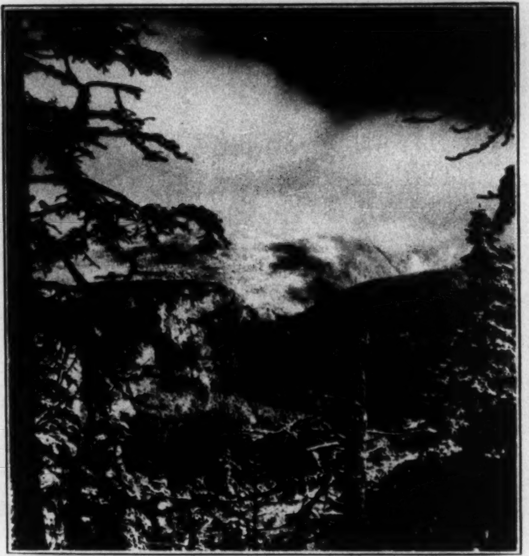


Fig. 2--Looking southeast from Cannon Mountain across Franconia Notch toward Mount Lafayette with Eagle Cliff and Eagle Pass in center [U. S. Forest Service]

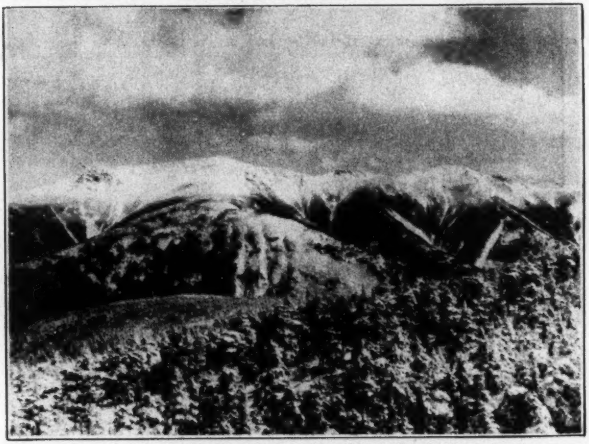


Fig. 3--Mount Lafayette from Cannon Mountain [New Hampshire Aerial Tramway Commission]

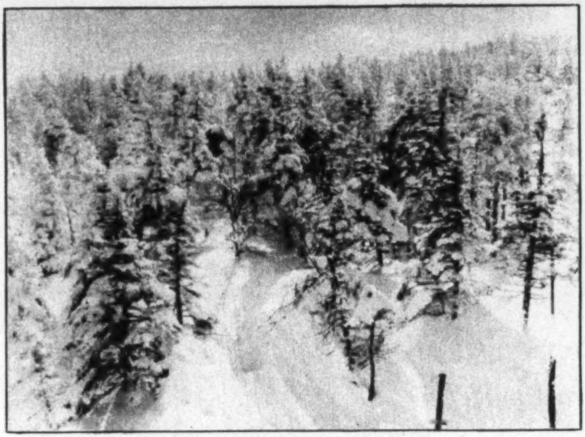


Fig. 4--14-foot drift at summit of Cannon Mountain
[New Hampshire Aerial Tramway Commission]

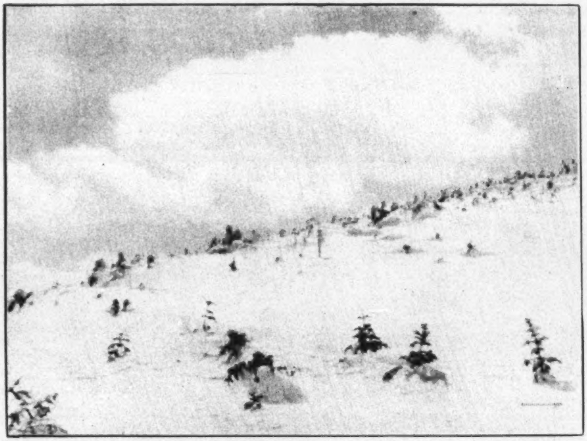


Fig. 5--Snowfield on southeast shoulder of Cannon Mountain at elevation 4,000 feet; snow-depth 10 to 20 feet
[New Hampshire Aerial Tramway Commission]

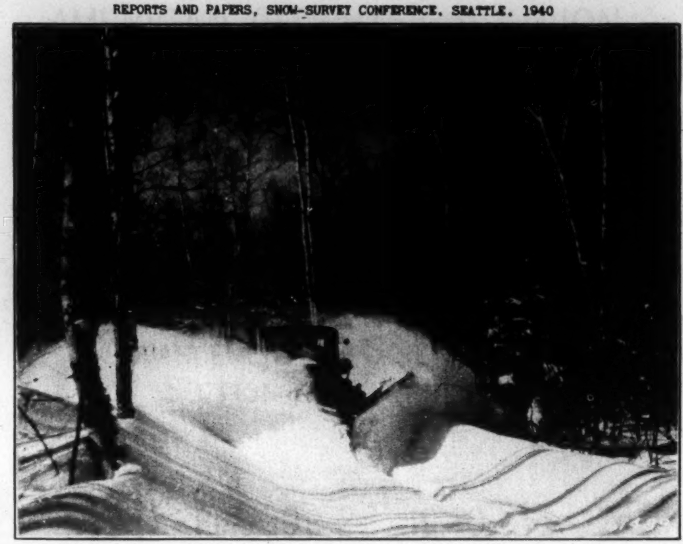


Fig. 6--Four-wheel-drive snow-plow in Bartlett Experimental Forest Road
[U. S. Forest Service]

Public Service Company of New Hampshire,
Manchester, New Hampshire

[Note: For index of names and of subjects in Part III-B, see page 1058 and following.]

AMERICAN GEOPHYSICAL UNION

JOINT REGIONAL MEETING

NORTH PACIFIC COAST AND
NORTH CONTINENTAL DIVIDE AREAS

WESTERN INTERSTATE SNOW-SURVEY CONFERENCE,
SECTION E AMERICAN ASSOCIATION FOR THE
ADVANCEMENT OF SCIENCE, AND
SECTION OF HYDROLOGY

June 19-22, 1940

PART III-C

SECTION OF HYDROLOGY

REPORTS AND PAPERS

Seattle, Washington
June 21, 1940

CONTENTS

JOINT REGIONAL MEETING AT SEATTLE, WASHINGTON, JUNE 21, 1940
SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

Reports and papers

Morning session, June 21, 1940

Page

Precipitation-characteristics west of the Cascade Mountains. FRED MERRYFIELD and VERNON WARREN 999
  Discussion. NORBERT LEUPOLD and ELMER FISHER 1004
Hydrological investigation for Mud Mountain Reservoir. GEORGE F. HOPKINS 1006
  Discussion. J. C. STEVENS and F. M. VEATCH 1011
Prospective dry years and their cause. HALBERT P. GILLETTE 1015
Story of electric service from the snow-fields to the home by the Washington Water Power Company: A sound film. (Joint lunch session)

Afternoon session, June 21, 1940

Measurement of foothill-springs to determine soil-moisture and ground-water conditions in Snake Basin, Idaho. JAMES C. MARR 1021
  Discussion. J. E. CHURCH 1027
Revised procedure for forecasting the spring runoff above Fort Peck. D. B. FREEMAN 1027
  Discussion. J. E. CHURCH and O. W. MONSON 1032
The snow-melt problem as affecting the design of flood control-works. OTTO N. RUGEN 1033
  Discussion. J. E. CHURCH and H. U. SVERDRUP 1044
Discussion of George W. Mindling's paper "Do climatological averages serve adequately as normals?". CLARENCE PEDERSEN 1046
  Discussion. H. T. GISBORNE 1050

Minutes of Seattle Meeting

Report, Chairman of Executive Committee, Western Interstate Snow-Survey Conference. H. P. BOARDMAN 1051
Personnel, Executive Committee, Western Interstate Snow-Survey Conference, 1940-42. 1052
Minutes of the Regional Meeting of the Section of Hydrology, American Geophysical Union, at Seattle, Washington, June 19-21, 1940. GEO. G. WEST, Secretary 1053
  Resolution on the use of the median instead of the average. 1053
  Appendix A--Record of 80 members and guests who attended the joint Regional Meetings of the Section of Hydrology, the Western Interstate Snow-Survey Conference, and the American Meteorological Society at Seattle, Washington, June 19-21, 1940. 1054

Index of names for Part III-C 1060
Index of subjects for Part III-C. 1060

REPORTS AND PAPERS, SECTION OF HYDROLOGY

PRECIPITATION-CHARACTERISTICS WEST OF THE CASCADE MOUNTAINS

Fred Merryfield and Vernon Warren

Ten years ago, the senior writer of this paper engaged in a discussion with a hydrologist on the distinction existing between predicting the flow of a river on which a power-plant was contemplated and predicting the flow of a river on which a power-plant existed. The difference between the two problems produced this paper, which is still unfortunately a progress-report. It was hoped to bring this study to a close at this time but unexpected circumstances rendered that goal impossible. It might be added however that the conclusion-study would not require the time or effort the material in this paper required.

The purpose of the work was to examine hydrological and meteorological data available in the area west of the Cascade Range in Oregon and Washington with a view to developing method or methods of forecasting actual river-flow. The suggestion for this method originated from the use of snow-surveys in predicting stream-flow. Books on hydrology contained methods for predicting flood-flows from runoff-areas, but little or no material was available to the writers for determination of predicting the probable future discharge.

Many attempts were made to predict the flow of the Willamette River from the runoff-records of the immediate past and, finally meeting with little success, these methods were abandoned. While the present flow of a river might give an indication of the flow for the next few weeks, it is apparent that the flow during the next few months is dependent upon the meteorological conditions which have prevailed during the past few months and will prevail in the immediate future. Precipitation then in whatever form is the most reliable indicator of river-flow. The area chosen for the study has a definite precipitation-period. Climatic, topographic, and geological factors which influence river-flow, while varying to some extent, do not materially affect the problem. A careful examination of the rainfall-data suggested that the variation in monthly rainfall was considerable at any station, month to month, and from one year to another and yet, there was a marked similarity between stations when these variations were expressed in percentages of the mean annual for that year.

A 30-year period from 1899 to 1929 was originally chosen, since this length of record would give a fairly accurate picture. Later this period was extended to 1939, thereby giving a 40-year period of observations for examination. The rainfall-year was arbitrarily assumed to start on September 1 and to end August 31. It is believed that in general this is well substantiated in most of the area studied. Only those stations were chosen whose records were unbroken and for that reason many of our major cities are included. It would have been excellent to use stations in the foothills and mountains but the records of these were broken and so would have detracted much from the study. Nine stations, west of the Cascade Mountains, and four east of the Mountains were examined. The latter study was made to prove that the rainfall of eastern Oregon and Washington was too erratic for use in prediction. Stations examined were: Astoria, Marshfield, and Aberdeen on the coast; Portland, Salem, Corvallis, Eugene, in the Willamette Valley in Oregon; Seattle and Vancouver in Washington. Jacksonville in the Rogue River Valley in southern Oregon was later added to the above group. East of the Cascades, the stations The Dalles, Pendleton, and Riverside in Oregon and Spokane in Washington were investigated.

The work consisted of totalizing monthly records for each year at each station. The totals represented the amount of rainfall that had fallen at that station from September 1 of that particular year to the end of the month in question. The accumulative percentage was computed for each month for each year at the chosen stations. The mean accumulative percentage for each month was then computed and plotted as ordinate against time in months as abscissa. The extreme high and low values of the accumulated per cent that ever happened in any month during the 40-year period were found and plotted as an envelope about the mean curve. Finally the probable deviations from the mean curve were computed and plotted. These latter curves show the probable rainfall distribution that might occur at the particular station in the 40-year period.

The computations of the probable deviation were made from the equation

$$e = 0.6745\ (C_v)$$

where e is the probable deviation and C_v is the coefficient of variation

$$C_v = \sqrt{(1/N)[t - (\bar{t})^2]}$$

where t = the value for any month, $\bar{t}$ = the mean value for that month, and N = number of years of record.

The plotted data bring out many interesting facts. The stations chosen west of the Cascades, with the exception of Jacksonville, have quite a uniform seasonal distribution of rainfall with small yearly variations. The curves are naturally skewed on both ends but since forecasts must be made sometimes between these periods, this fact is relatively unimportant. It is interesting to note the slight variations between the stations for the mean curve. An examination of Table 1 below will bring out this point.

Table 1

Month	Mean curve for						
	Astoria	Portland	Vancouver	Seattle	Corvallis	Salem	Eugene
September	4.1	4.7	5.1	5.0	4.0	4.6	5.0
October	12.3	11.9	12.5	13.5	11.2	12.3	12.5
November	26.8	27.6	28.4	28.7	27.6	27.7	27.7
December	43.5	44.7	44.9	45.0	45.0	45.1	43.0
January	59.6	59.8	59.6	60.3	61.5	60.2	57.7
February	71.5	71.6	71.3	71.3	74.4	72.8	70.3
March	82.4	82.0	80.8	80.2	85.2	83.2	80.8
April	88.9	88.5	87.5	86.3	91.0	89.4	87.8
May	93.4	93.4	92.5	91.5	95.3	94.0	93.8
June	97.0	97.1	96.8	95.9	98.2	97.5	97.9
July	98.5	98.7	98.0	97.7	99.0	98.6	99.0
August	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The cities of Portland, Salem, Eugene, Astoria, Corvallis, and Vancouver compare very favorably. Seattle's distribution is slightly different. A larger percentage of rain falls during the months of August at Seattle. The possible and probable deviation-curves also show similar characteristics as can be seen by a study of Table 2. Using Seattle for illustration it is seen that the probable percentage of rainfall that has occurred until the end of February is limited between 84.2 as a maximum and 76.2 as a minimum. It is interesting to note that Corvallis shows generally higher maximum and minimum possible values than the remainder. All other stations are in much closer agreement.

The year 1900-01 at all stations falls within the maximum and minimum probable-deviation curves in all months except September and June. In each case the rainfall for that year was above the normal for the period of record. Comparison of the station-records for the same years, while not fully investigated, leads the authors to believe that variations in percentages in the months from January to August is not too great to be of value in forecasting. Several years were chosen at random from the period of record and marked similarities were noted. For example, in the year 1910-11 the percentages for the month of February are: Astoria, 77.8; Portland, 78.3; Vancouver, 76.6; Seattle, 80.5; Corvallis, 78.1; Salem, 80.7; and Eugene, 79.1. Another year chosen in the same way gives wider variations. The year 1931-32 shows the following percentages for the same month as above: Astoria, 67.7; Portland, 70.7; Vancouver, 70.2; Seattle, 69.9; Corvallis, 72.5; Eugene, 64.6; and Salem, 70.

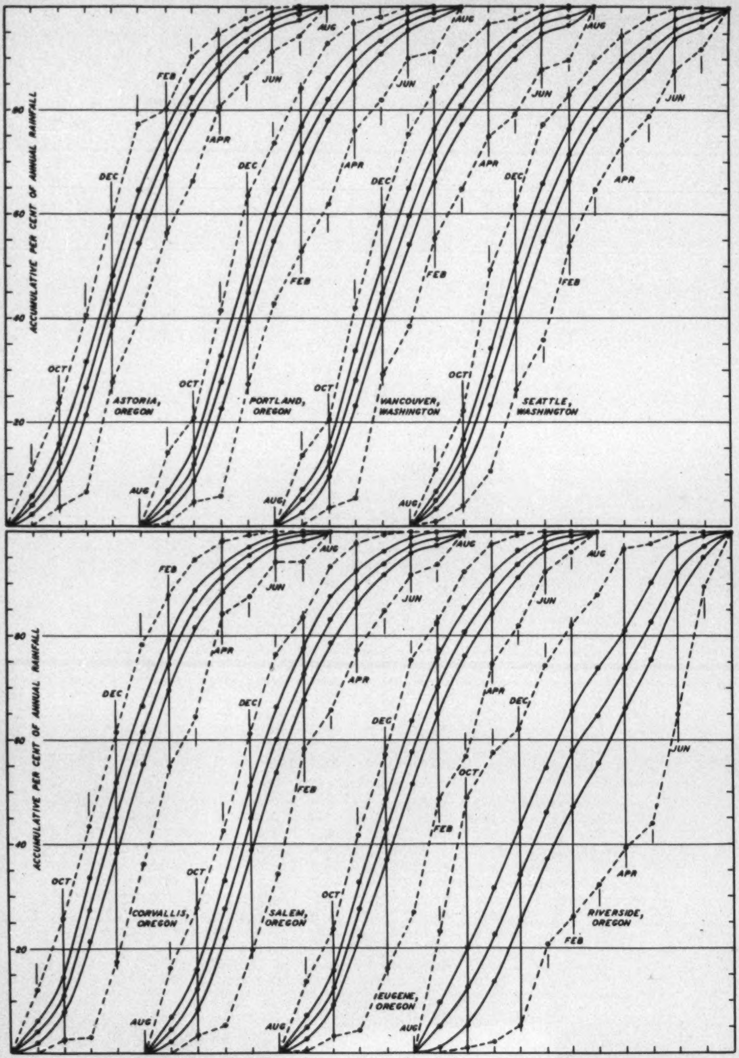
An interesting study was made of the separate ten-year periods for each station, beginning with 1899-1901 to 1908-09 and ending with 1929-30 to 1938-39. The months of February and March are chosen for the sake of saving space. Comparison of the ten-year average of the month of February shows 74.4, 74.0, 76.2, and 72.8 per cent. Similar comparison for the month of March shows 86.0, 83.7, 86.4, and 83.8 per cent. The above figures were taken from the Corvallis record. Similar data appear for the remaining stations.

The years in which the maximum ten deviations were found and are reproduced in Table 3 for the months of January, February, and March.

According to Table 3, the accumulative percentage of rainfall occurring from the month of September, 1910, to the end of January, 1911, was among the upper ten deviations for all stations. The numbers 1, 2, and 3 at the head of the columns refer to (1) all seven stations, (2) all stations except Astoria and Seattle, (3) Salem, Corvallis, and Eugene. In a general way this indicates that for these same seven stations the maximum accumulative percentages of rainfall are very similar in the same years for all stations.

Table 2

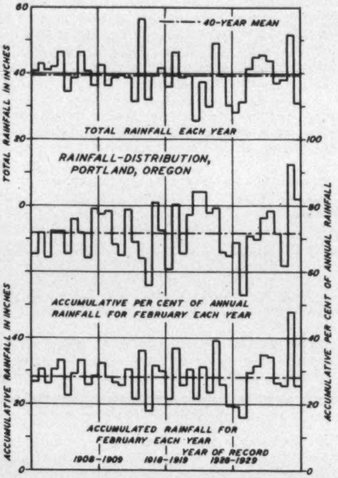
Month	Astoria	Portland	Vancouver	Seattle	Corvallis	Salem	Eugene
Maximum probable curve							
September	5.6	6.8	7.3	6.8	6.2	7.0	7.4
October	15.8	15.0	15.5	16.6	14.6	16.1	15.9
November	32.2	32.6	33.7	34.2	33.5	33.3	32.9
December	48.4	50.0	49.8	50.7	51.7	51.2	48.9
January	64.6	64.8	65.0	65.9	67.6	66.4	63.8
February	75.5	76.7	76.4	76.3	79.1	77.8	75.6
March	85.6	86.2	84.5	84.2	88.8	87.6	85.4
April	91.4	92.0	91.0	89.7	93.6	92.6	91.3
May	95.7	96.0	95.3	94.3	97.2	96.3	96.4
June	98.4	98.8	98.8	97.8	99.3	99.0	99.1
July	99.6	100.0	99.8	99.1	100.0	99.7	99.8
August	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Minimum probable curve							
September	2.4	2.6	2.9	3.2	1.8	2.2	2.6
October	8.8	8.8	9.5	10.4	7.8	8.5	9.1
November	21.4	22.6	23.1	23.2	21.7	22.1	22.5
December	38.6	39.4	40.0	39.3	38.3	39.0	37.1
January	54.6	54.8	54.2	54.7	55.4	54.0	51.6
February	67.5	66.5	66.2	66.3	69.7	67.8	65.0
March	79.2	77.8	77.1	76.2	81.6	78.8	76.2
April	86.4	85.0	84.0	82.9	88.4	86.2	84.3
May	91.1	90.8	89.7	88.7	93.4	91.7	91.1
June	95.6	95.4	94.8	94.0	97.1	96.0	96.7
July	97.4	97.4	96.2	96.3	98.0	97.5	98.2
August	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Maximum possible curve							
September	10.9	14.1	13.6	10.7	12.1	16.4	13.7
October	23.8	20.8	20.6	22.7	25.8	27.8	23.8
November	40.7	41.4	42.0	49.4	43.3	42.7	41.9
December	59.8	63.5	60.2	61.8	61.4	61.2	57.5
January	77.3	73.5	75.3	77.4	78.3	76.4	75.3
February	80.2	84.2	83.5	83.0	87.7	83.5	82.6
March	90.2	92.8	91.5	89.3	94.5	93.3	92.3
April	94.7	96.6	96.5	94.5	98.0	97.5	97.5
May	97.7	97.9	97.5	97.9	99.1	99.4	99.3
June	99.6	99.9	100.0	99.6	100.0	100.0	100.0
July	99.9	100.0	100.0	100.0	100.0	100.0	100.0
August	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Minimum possible curve							
September	0.0	0.3	0.1	0.6	0.0	0.0	0.3
October	3.8	4.5	3.9	3.9	2.6	3.7	3.4
November	6.7	5.7	5.5	10.5	3.2	5.1	4.4
December	27.9	27.3	29.4	26.4	17.5	19.9	16.1
January	39.9	42.9	38.6	35.9	36.3	34.3	27.0
February	56.4	52.9	55.4	53.7	54.9	58.4	48.7
March	66.7	61.8	64.8	64.6	64.5	65.8	57.0
April	80.6	76.0	74.6	73.5	84.3	77.3	74.5
May	86.3	82.0	79.1	79.0	87.4	84.9	82.0
June	91.2	89.9	87.8	88.0	94.1	91.8	92.4
July	94.1	91.1	89.7	91.9	94.2	93.5	96.0
August	100.0	100.0	100.0	100.0	100.0	100.0	100.0



ACCUMULATIVE PER CENT OF ANNUAL RAINFALL BY MONTHS, 1899-1900 TO 1938-1939
– – –•– – –•– – MAXIMUM AND MINIMUM; ——•——•—— 40-YEAR MEAN; ——•——•—— PROBABLE DEVIATION

Table 3

Year	January			Year	February			Year	March		
	(1)	(2)	(3)		(1)	(2)	(3)		(1)	(2)	(3)
1911	7	5	3	1909	7	5	3	1909	7	5	3
1934	7	5	3	1924	7	5	3	1935	7	5	3
1935	7	5	3	1925	6	5	3	1938	7	5	3
1923	6	4	2	1927	6	5	3	1918	6	5	3
1925	5	4	2	1921	5	5	3	1924	6	5	3
1903	4	4	3	1910	5	4	3	1904	6	4	2
1938	4	2	1	1918	5	4	3	1934	6	4	2
1910	3	3	3	1911	5	4	2	1921	5	5	3
1921	3	3	3	1914	3	2	0	1922	3	2	2
1913	3	1	0	1926	2	2	2				



Conclusions--Time does not permit to study the rainfall-statistics more closely at the present due to urgency of other matters, but it is hoped that time will be available in the near future to complete the work.

(1) It can be concluded that the rainfall of the Pacific Northwest north of Eugene and west of the Cascade Mountains shows similarity throughout the lowland part of the area, especially when the accumulative rainfall is expressed as a percentage of the total rainfall of each year. The year in this case refers to the period from September 1 to August 31.

(2) The mean accumulative percentage of rainfall for the month of February varies from 70.3 per cent at Eugene to 74.4 per cent at Corvallis.

(3) The maximum probable accumulative percentage of rainfall for the same month varies from 75.5 per cent at Astoria to 79.1 per cent at Corvallis.

(4) The probable minimum varies from 65.0 per cent at Eugene to 69.7 per cent at Eugene.

(5) The maximum percentage of rainfall that has occurred in the period in the month of February was 80.2 per cent at Astoria and 87.7 per cent at Corvallis.

(6) The minimum percentage of rainfall that has occurred in the period in the month of February was 57 per cent at Eugene and 66.7 per cent at Astoria. In the above, the figures quoted are the extremes for the area.

(7) The year from September, 1900, to August, 1901, fell within the maximum and minimum probable curves for each of the seven stations.

(8) Jacksonville in southern Oregon shows greater deviation than the seven stations listed in the Tables.

(9) Stations east of the Cascade Mountains--Spokane, The Dalles, Pendleton, and Riverside--show no correlation which might be useful for further studies.

(10) Future work will be made on the total rainfall occurring up to the end of January, February, and March in the hope that it will yield some clue as to the percentage of rainfall that might have occurred.

(11) If the study, mentioned in (10), yields results, then it should be possible to use this to advantage in forecasting the flow of some particular river.

Oregon State College,
Corvallis, Oregon

DISCUSSION

NORBERT LEUPOLD (U. S. Engineer Office, Portland, Oregon)--The authors are to be commended for the interesting analysis that they have made. It represents a great amount of work and is a contribution to our gradually accumulating fund of knowledge and ideas. It is one more step in contradicting the remark attributed to Mark Twain that everyone talks about the weather but no one ever does anything about it. With the conclusions of such a study at hand, we can know at least a little something of what we are talking about and can anticipate the weather even though it may be impossible to do anything about it in the way of changing or controlling it.

The paper elucidates a phenomenon with which all those who live in the Pacific Northwest are familiar, that is, the stability of the rainfall-cycle. In the eight months from September to April, about 90 per cent of the precipitation occurs and 60 per cent has occurred up to February 1. The percentage-distribution during both dry years and wet years is relatively pretty much the same as for an average year. The envelope-curves of maximum and minimum values inclose a ribbon of plus or minus three standard deviations from the mean. Theoretically 99.87 per cent of all values may be expected to fall within these limits. In view of the large percentage of precipitation prior to February 1, it appears that forecasting on that date of the remaining precipitation to be expected in the climatic year should be fairly reliable.

The correlation between precipitation and stream-flow remains to be worked out, as does the possible distribution of precipitation. Some of the things that must be considered in that study are:

(1) The division of the runoff into that due to surface-runoff from precipitation, that due to ground-water flow, and that from melting snow in the mountains--Of course, these last two are the most important, particularly the ground-water flow which has been recharged during the winter rainy season and which is the principal, if not the only, source of flow for late spring and summer months. In any forecast of runoff, this ground-water flow due to precipitation preceding the forecast date will be the base-flow. Additional flow due to estimated precipitation must be added to the base-flow to arrive at a forecasted flow.

(2) The probable distribution of forecasted precipitation during the season--An example of the vagaries that enter into the problem is the storm of March, 1931, which resulted in one of the largest April floods of record on the Willamette River. Using the data at Portland, on March 1 precipitation was only 56 per cent of normal. However, the precipitation during March was 210 per cent, during June was 200 per cent, and for the climatic year 1930-31 was 75 per cent of normal. Forecasting these results on March 1 would have required a crystal ball.

The per cent of normal rainfall in the Willamette Valley also is useful in anticipating the probable occurrence of a storm with its resultant flood. A number of years ago the writer, in searching for some means of forecasting or anticipating the occurrence of a flood during the rainy season, made an analysis of what he termed the rainfall-index, which is only a short name for the percentage of normal rainfall up to any given date, and the occurrence of floods. The results of that study are briefly as follows: If the flood-discharges at Albany are plotted against values of the rainfall-index at Eugene, it is observed that during the period of record the larger floods in the months of January, February, March, and April have occurred with values of the index in excess of 100 per cent, and the largest ones have occurred with an index of between 100 and 110. There is nothing remarkable about this for, obviously, it takes rain to produce floods on the Willamette River and if such rains come during a generally rainy season, such as would accompany a rainfall-index of 100 or more, infiltration would be reduced, runoff would be greater, and the flood would be higher. However, this index is of some value in anticipating the possibility of a flood. It could be used as one of the considerations in the operation of a multiple-use flood-control reservoir such as those of the Willamette project, wherein the flood-reservation is decreased during the spring. The general problem of predicting floods on the Willamette is a part of the precipitation-characteristics of the Basin, and I recommend it to authors for inclusion in their future studies.

ELMER FISHER (U. S. Weather Bureau, Portland, Oregon)--The Willamette drainage slightly exceeds 11,000 square miles.

It will be noted that Mr. Merryfield has chosen the water year from September 1 to August 31 of the following year. It will be further noted that the forecast-scheme, which in reality is an empirical method, is based on the amount of precipitation that has occurred from September 1 to February, inclusive. According to the normals for the stations considered in Table 1 for the mean curve, by the end of February from 70 per cent to 76 per cent of the annual amount of precipitation for the water year may be expected to have occurred and by the end of March from 79 per cent to 85 per cent of the annual amount may be expected to have occurred. Accordingly the forecaster would only be required to forecast from 24 per cent to 30 per cent to achieve a perfect score. The fact that a certain amount of precipitation has occurred is no criterion that more will occur.

Table 1--Normal monthly precipitation

Month	Astoria	Portland	Vancouver	Seattle	Corvallis	Salem	Eugene
September	3.33	1.98	1.99	1.77	1.71	1.73	1.99
October	6.27	3.12	2.69	2.84	2.91	2.90	2.73
November	11.31	6.10	6.08	5.03	6.92	5.89	5.89
December	12.28	6.72	5.56	5.60	6.63	5.84	5.72
January	12.09	6.60	5.39	4.94	6.54	5.33	5.42
February	9.43	5.36	4.44	3.89	5.32	4.57	4.65
Sum, September to February	54.71	29.88	26.15	24.07	30.03	26.26	26.40
Normal annual	76.57	41.62	36.80	34.03	40.27	36.13	37.57
Per cent annual September to February	71	72	71	71	75	73	70
March	8.04	3.91	3.35	3.05	4.19	3.65	3.90
Sum, September to March	62.75	33.79	29.50	27.12	34.22	29.91	30.30
Per cent annual September to March	82	81	80	80	85	83	81

From September to February, inclusive, 70 per cent to 75 per cent of annual precipitation may be expected to have occurred.

From September to March, inclusive, 79 per cent to 85 per cent of annual precipitation may be expected to have occurred.

Table 1--It seems as though a knowledge of the form of precipitation that has already occurred, whether snow or rain, might be as desirable as knowing the total amount to be expected after February. The snow-cover, while of rather limited area, is very important. During the winter of 1939-40 the snow-cover in the Cascade Mountains was comparatively light. The result is that stages of the Willamette and tributaries are lower than those that usually occur a month later.

Table 2--Monthly precipitation and departure, September to March 1939-40 portion of water-year

Month	Astoria		Portland		Vancouver		Seattle		Corvallis		Salem		Eugene	
	Amt.	Dep.	Amt.	Dep.	Amt.	Dep.	Amt.	Dep.	Amt.	Dep.	Amt.	Dep.	Amt.	Dep.
September, 1939	0.91	-2.42	0.60	-1.38	0.44	-1.55	1.30	-0.47	0.43	-1.28	0.38	-1.35	0.70	-1.29
October, 1939	5.18	-1.09	2.14	-0.98	2.42	-0.27	2.25	-0.59	2.90	-0.01	2.63	-0.27	3.07	+0.34
November, 1939	5.47	-5.84	1.73	-4.37	1.77	-4.31	2.75	-2.28	0.31	-6.61	0.84	-5.05	0.51	-5.38
December, 1939	14.65	+2.37	8.37	+1.65	8.61	+3.05	10.41	+4.81	8.53	+1.90	10.32	+4.48	6.00	+0.28
January, 1940	5.97	-6.12	2.36	-4.24	2.88	-2.51	3.10	-1.84	4.41	-2.13	4.75	-0.58	4.52	-1.00
February, 1940	15.66	+6.23	10.82	+5.46	10.52	+6.08	6.65	+2.76	9.80	+4.24	11.66	+7.75	9.97	+5.44
Sum	47.84		26.02		26.64		26.46		26.38		30.58		24.77	
Per cent annual normal	62		63		72		78		66		85		66	
March, 1940	9.53	+1.49	5.12	+1.21	4.26	+0.91	4.39	+1.34	4.93	+0.61	5.94	+2.60	4.38	+0.44
Sum, September to March	57.37		31.14		30.90		30.85		31.31		36.52		29.15	
Per cent Annual normal	75		75		84		91		78		101		78	

Regardless of percentages of annual amount of precipitation that have already occurred, the stages in the Willamette above Oregon City, Oregon, are lower as of June 1, 1940, than those that usually occur a month to a month and one-half later.

Table 2--Effective precipitation west of the Cascades, that is, precipitation that is reflected almost immediately in stream-flow, occurs mostly in periods generally varying from a week to ten days in length.

It would appear that the solution of the problem would be a storm-forecast which includes the intensity and duration. The Hydrometeorological Section of the Weather Bureau, it is understood, has met with some very gratifying success in this line.

The precipitation-pattern in northwestern Oregon is generally quite evenly distributed although the intensity may vary considerably. It has been noted that the number of days with 0.01 inch or more precipitation on the coast is reflected very closely in the number of days with precipitation in the Willamette Valley.

HYDROLOGICAL INVESTIGATION FOR MUD MOUNTAIN RESERVOIR

George F. Hopkins

The Seattle District of the United States Engineer Office, because of its responsibilities in connection with Federal flood-control activities, is vitally interested in the hydrology--especially in the flood-hydrology--of the streams in its district. That interest is particularly serious in the case of the White River on which the Engineer Office is now constructing a flood-retention reservoir which, with certain channel-improvements in the delta-area, is designed to furnish almost complete flood-protection to the thickly populated White-Puyallup Valley.

The White River Basin above Mud Mountain Dam covers an area of 403 square miles, and varies in elevation from about 850 feet at the dam-site to 14,408 feet at the summit of Mt. Rainier. The topography is extremely rugged and at few points in the Basin is bed-rock more than a few feet below the surface. Because of these conditions infiltration is probably negligible, and concentration of surface-runoff into the stream-channels is rapid.

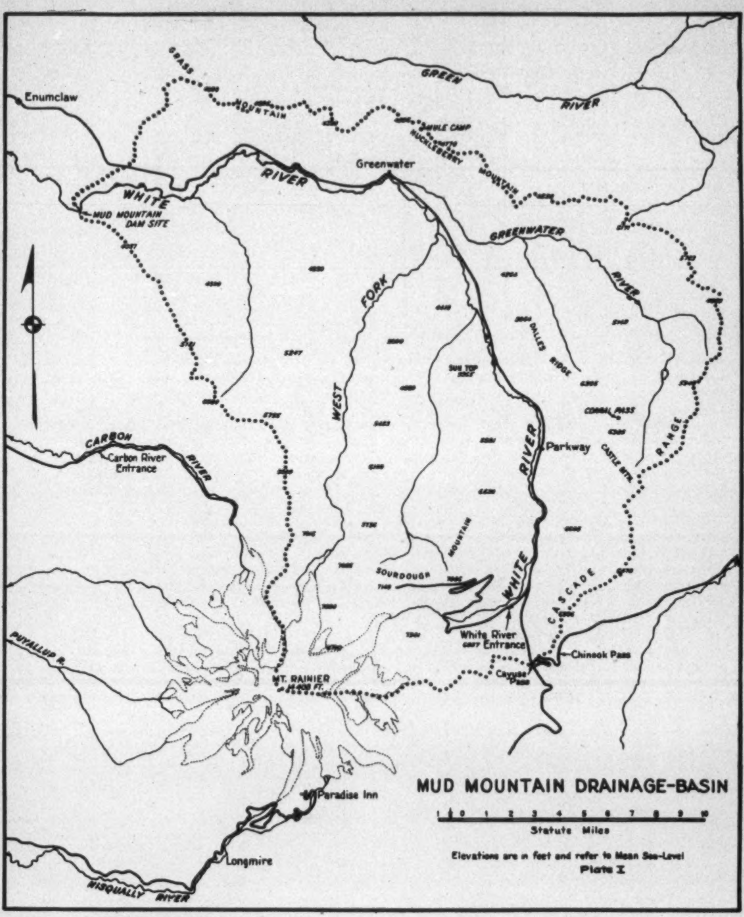
The permanent population of the Basin, aside from the construction forces at Mud Mountain, is not over 50 persons. Access to the valley is possible by only one highway. That road extends up the valley-floor from the dam-site for about 30 miles and then divides, one branch extending southerly into the Cowlitz River Basin at Cayuse Pass (elevation 4,700 feet) then easterly over the Cascade Mountains at Chinook Pass (elevation 5,440 feet) and the other westerly up the flanks of Mount Rainier to Sunrise Lodge (elevation 6,500 feet). The road is open to winter travel only to the fork, or a little beyond, although there is good reason to believe that the increasing popularity of snow-sports may lead, within a few years, to an attempt to keep the roads open to a higher elevation. United States Forest Service and Park Service trails lead from the roads to all parts of the Basin, but many of them are difficult to travel at any time and well-nigh impossible, even for experienced mountaineers, during the snow-season.

Major floods on this stream, as on all streams of the Puget Sound area, occur almost without exception during November to March, and are augmented to a marked degree by the rapid melting of the heavy mantle of snow that normally covers the higher portions of the area during those months. Obviously, therefore, any investigation into the flood-hydrology of the Basin must include the determination not only of the precipitation that falls during the flood-period but also of the antecedent precipitation stored in the form of snow and of the factors that accelerate or retard its melting. So far as is known to the writer, no systematic attempt at snow-surveying has ever been made in the Puget Sound Basin, with the exception of the surveys made by the city of Tacoma in the catchment-area of its Cushman Dam on the eastern slope of the Olympic Range.

The available precipitation-data for the Puget Sound Basin indicate that below elevation 2,000 feet snowfall is light and of little consequence in flood-production, that above elevation 6,000 feet, more or less, but little snow melts during the winter months, and that, at least within the same range of elevation, rainfall increases with altitude. In other words, between elevations 2,000 feet and 6,000 feet lies the zone in which precipitation is most intense and from which winter runoff from melting snow may be large.

Plate II shows, for the White River Basin above Mud Mountain Dam, the drainage-area by altitude-zones. It will be seen from Plate II that approximately 90 per cent of the Basin lies below elevation 6,000 feet and that almost 50 per cent lies between elevations 3,000 feet and 5,000 feet.

In this Basin there were, when construction of the Mud Mountain Dam was authorized by Congress, no recording precipitation-gages and but one non-recording gage--at Parkway (elevation 2,630 feet). Recording gages were maintained at Tacoma, 28 miles west of the dam-site, and at Seattle, 36 miles northwest of the site. The United States Geological Survey maintained water-stage recorders on White River just upstream from the mouth of Greenwater River, and on Greenwater River near its mouth, which together measured the runoff from 291 square miles of the


Enumclaw
GRASS MOUNTAIN
GREEN RIVER
MULE CAMP
HUCKLEBERRY MOUNTAIN
Greenwater
WHITE RIVER
MUD MOUNTAIN DAM SITE
GREENWATER RIVER
WEST FORK
DALLES RIDGE
SUN TOP
CORRAL PASS
CASTLE MTN
RANGE
CARBON RIVER
Carbon River Entrance
Parkway
WHITE RIVER
SOURDOUGH MOUNTAIN
White River Entrance
CASCADE
Chinook Pass
Cayuse Pass
PUYALLUP R.
MT. RAINIER 14,408 FT.
Paradise Inn
Longmire
NISQUALLY RIVER
1 0 1 2 3 4 5 6 7 8 9 10
Statute Miles

MUD MOUNTAIN DRAINAGE-BASIN

Elevations are in feet and refer to Mean Sea-Level

Plate I

Basin, and on Puyallup River at Puyallup where the runoff from 914 square miles of the combined White and Puyallup rivers was measured.

In the late fall of 1938 the writer was assigned the task of installing additional hydrological equipment in the Basin, for the dual purpose of gathering data on the hydrology of the Basin and of determining, if possible, the effect of snow-melt on flood-discharges of Puget Sound streams. Theoretical considerations suggested that sites for precipitation-stations and snow-courses should be so selected that they would sample the entire range of altitudes up to about 6,000 feet, would give adequate areal coverage to the entire Basin, and would be about equally divided between northeast and southwest slopes, that is, between the slopes exposed to and

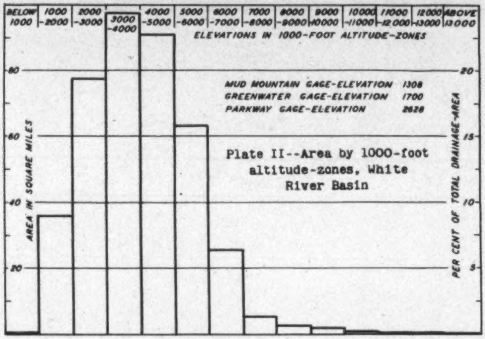


Plate II--Area by 1000-foot altitude-zones, White River Basin

shielded from the prevailing southwest-storm winds; and that stream-gaging stations should be so located that the flood-runoff from each of the more important tributary streams could be determined.

Because of the inaccessibility of most of the Basin, practical necessity has much modified theoretical consideration in the selection of climatological stations and of snow-courses. It was apparent that the type of data we needed could be secured only by recording instruments and that such instruments, if they were to be properly maintained, must be located near a permanent habitation--which meant, of course, that they could be located only on the valley-floor.

Three locations suitable for precipitation-gages were found: One at the dam-site (elevation 1,310 feet), one at Greenwater (elevation 1,710 feet), and one at Parkway (elevation 2,630 feet). At each of these locations there was installed, in January, 1939, a recording precipitation-gage of nine inches capacity, a thermograph, and one or more storage snow-gages. No changes have since been made in those installations except that during the winter of 1939-40 the thermographs were replaced by hygro-thermographs loaned, for the winter season, by the Seattle Office of the United States Weather Bureau.

The number of snow-courses available was limited by the consideration that either they must be near enough to the road that the surveys could be completed and the surveyors could return to

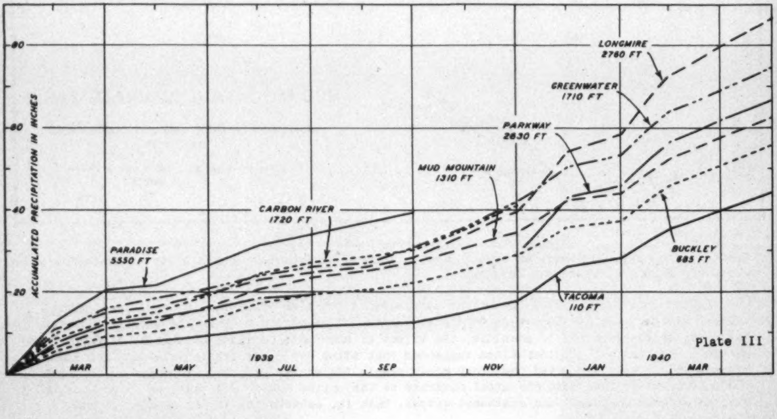


Plate III

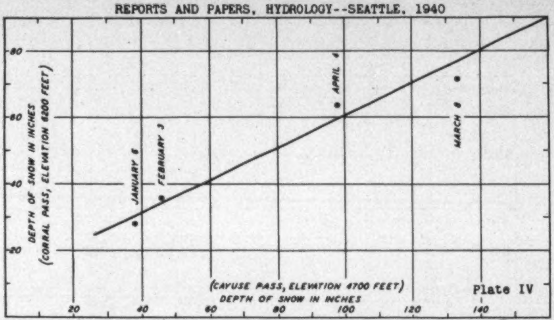


Plate IV

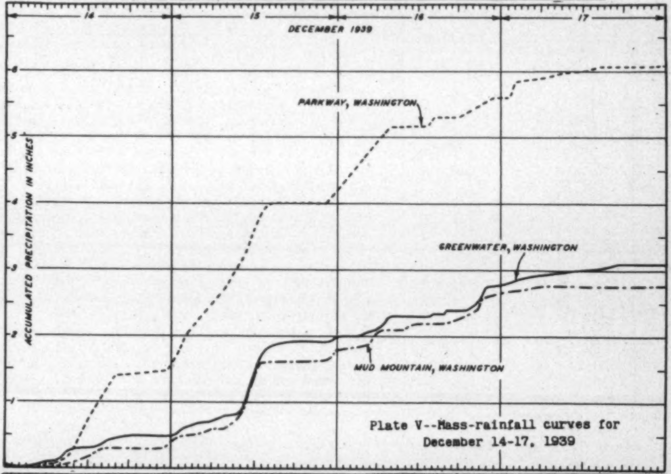


Plate V--Mass-rainfall curves for December 14-17, 1939

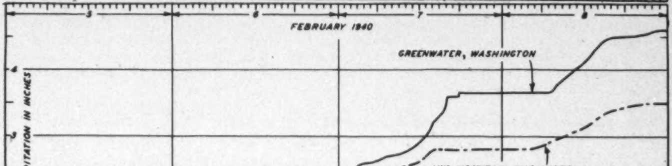


Plate VI--Mass-rainfall curves for February 5-8, 1940

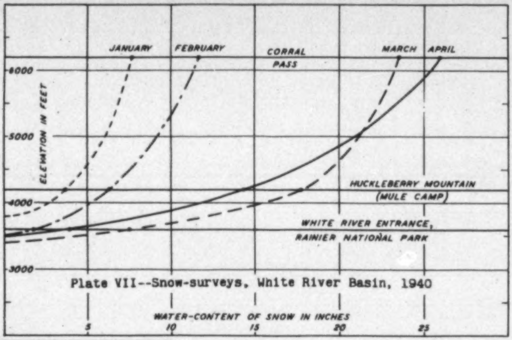


Plate VII--Snow-surveys, White River Basin, 1940

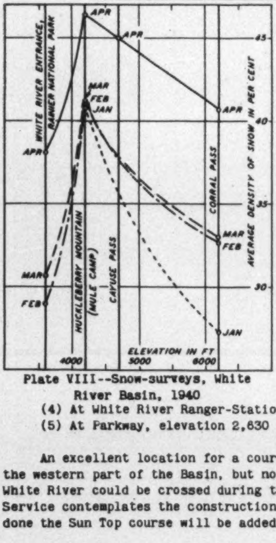


Plate VIII--Snow-surveys, White River Basin, 1940

the road in one day, or that they be placed where overnight shelter was available. These limitations reduced the number of possible courses to five, as follows:

(1) Corral Pass, elevation 6,200 feet, in the eastern part of the Basin and on the divide between White River and its largest tributary, Greenwater River. At this location a Forest Service shelter-cabin has been made available for the use of the surveyors.

(2) At Cayuse Pass, elevation 4,700 feet, on the highway and on the divide between White River and the Cowlitz River to the south. Cayuse Pass, easily reached by ski-trail from the end of the winter road, is a popular snow-sport area and it was believed, therefore, that it would be difficult to maintain an untrampled course there. Our experience during the past winter, however, has convinced us that in the future a course must be observed somewhere near the pass even though such a course may not be altogether satisfactory.

(3) At Mule Camp, elevation 4,200 feet, on Huckleberry Mountain at the northern watershed of the Basin. The survey of this course can, with little difficulty, be made in one day.

(4) At White River Ranger-Station, elevation 3,000 feet, near the end of the winter road.

(5) At Parkway, elevation 2,630 feet, near the lower limit of snow-storage.

An excellent location for a course was found at Sun Top Mountain, elevation 5,200 feet, in the western part of the Basin, but no shelter is available there, nor is there a bridge by which White River could be crossed during the snow-season. It is understood, however, that the Forest Service contemplates the construction of both the bridge and a shelter-cabin, and when that is done the Sun Top course will be added.

The remainder of the Basin, comprising well over one-half of the catchment-area, is entirely inaccessible during the snow-season and probably will remain so for many years to come.

Snow-surveys are made on or about the first of each month from November to April, with additional surveys at other times if any unusual climatological conditions indicate a necessity for them. The surveyors carry, in addition to the usual equipment, an aneroid barometer and a psychrometer so that variations of temperature, humidity, snow-depth, etc., with altitude may be observed during the course of the surveys.

Inasmuch as the two main stems of the river system--White River and Greenwater River--were already being gaged by the United States Geological Survey, the establishment of only one additional stream-gaging station was required. That station has been constructed immediately below the dam-site. The control is apparently permanent, the measuring section satisfactory, and frequent current-meter measurements are made by the Geological Survey, so it is anticipated that the stream-flow determinations will be complete and accurate.

This, then, is the instrumental equipment with which the hydrology of the Basin is being studied: Three precipitation- and temperature-stations; five snow-courses; and three stream-gaging stations. It is realized that the present facilities are entirely inadequate for an accurate determination of precipitation and snow-storage, but no feasible method of extending them, except at exhorbitant cost, is now apparent. The writer would welcome suggestions from fellow hydrologists as to methods of increasing the value of the investigation not only to the solution of the immediate problem but also to the needs of other investigators of similar phenomena.

The records thus far assembled cover too short a period to permit any definite conclusions to be drawn from them. Nevertheless they do indicate, in a general way, certain phenomena that may be of interest to hydrologists. To conserve time these data are presented in graphical form.

Plate III presents mass-curves of monthly precipitation for the period February, 1939, to April, 1940, for stations in and near the Basin. It indicates that precipitation increases rapidly with altitude except as affected by the "rain-shadow" of high mountains. Thus Parkway, which lies almost directly northeast of the summit of Mount Rainier, and is therefore sheltered from the southwest-storm winds, receives less precipitation than do Greenwater and Carbon River entrance, both of which are almost a thousand feet lower in elevation, and only about 75 per cent as much as Longmire which is at practically the same altitude. The same trend is shown by Plate IV, which indicates depth of snow (corresponding roughly to total winter precipitation) at Corral Pass and at Cayuse Pass. Corral Pass, which lies directly in the rain-shadow of Mount Rainier, shows only 60 per cent of the snow-storage indicated at Cayuse Pass, on the edge of the rain-shadow, although it is at an elevation 1,500 feet higher.

Plates V and VI, which show mass-curves of precipitation for two periods of moderately intense rainfall at Mud Mountain, Greenwater, and Parkway, indicate how erratic the distribution of mountain rainfall may be over a small area. Thus in the storm of December 14-17, 1939, Parkway received more than twice the precipitation recorded at Mud Mountain or Greenwater, whereas in the storm of February 5-8, 1940, the precipitation at Parkway was only 60 per cent of that at Mud Mountain and only 46 per cent of that at Greenwater.

Plate VII summarizes the results of the snow-surveys for the past winter. It indicates a fairly uniform increase of snow-storage with increasing elevation. Attention is invited to the fact that the April survey reveals a lowering of the snow-storage during March below about elevation 5,000 feet, and an increase above that elevation, thus indicating that in the Cascade Range conditions are roughly similar to those reported by Mr. Edgar H. Fletcher [Melting snow as a flood factor in the Sierra Nevada, Bull. Amer. Met. Soc., February, 1940] for the Sierra Nevadas. "As a flood-factor, a deep snow-cover above the 5,000-foot contour becomes increasingly less important with increase in elevation. The greatest contribution of water from melting snow is between the 3,500 and 5,000-foot elevations."

Plate VIII shows the average densities of the snow-cover at the snow-courses for the surveys of 1939-40. The reason for the much higher density at the intermediate elevation is not clear. It is possible that it is due to the exposure of the Mule-Camp course, but the one measurement at Cayuse Pass (in April) would seem to indicate that snow-densities increase with elevation up to about 4,000 feet and decrease above that elevation.

U. S. Engineer Office,
Seattle, Washington

DISCUSSION

J. C. STEVENS (Consulting engineer, Portland, Oregon)--Even though the hydrologic investigations of the Mud Mountain Area are incomplete and but few data have as yet been secured, nevertheless if dams are to be built--and this one is under construction--some data to serve as a basis for design must be had. The value of Mr. Hopkins' paper would have been enhanced had he given the processes by which the design-flood of 60,000 cfs for the construction period, and 135,000 cfs for subsequent flood-control service, were arrived at.

It is easy to arrive logically at design-floods if hydrologic data are complete and extend over a goodly term of years. But it takes real engineering skill to pick a design-flood from among a few scattering dabs covering only a year or two. Even picking one out of thin air is not to be entrusted to a novice and one so plucked by an experienced manipulator may have much to recommend it and even command our respect. I cannot fill the gap but I can show you how the reservoir will behave when these record floods come.

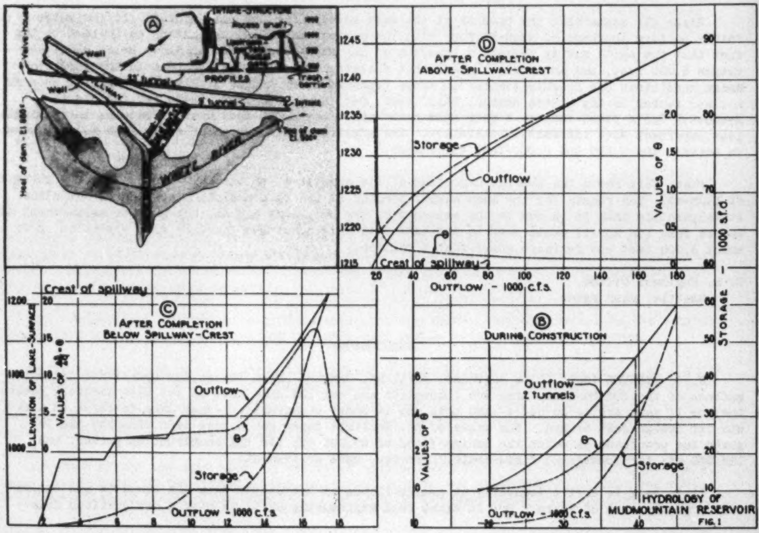
Figure 1A shows the general plan of Mud Mountain Dam, its spillway and tunnels and a profile of the entrance to the 23-foot tunnel.

Two periods are to be considered, during construction and subsequent service. During construction the storage-capacity is as given in (B) showing a maximum of about 58,000 sfd. The actual capacity would of course depend upon how high the Dam could hold water at the time of the occurrence of the flood. The outflow-capacity of the two tunnels is also shown in terms of storage-capacity. The θ-curves were for flood-routing purposes and need not be explained here [see Proc. Hydraulic Conf. Pacific Div. U. S. Eng. Corps, San Francisco, February 26-27, 1940].

After completion of the dam and spillway the storage- and outflow-capacities are indicated in (C) up to the spillway-crest and above that altitude in (D). It shows that at 1,245 the storage-capacity is 90,000 sfd and the discharging capacity of spillway and tunnels is 188,000 cfs.

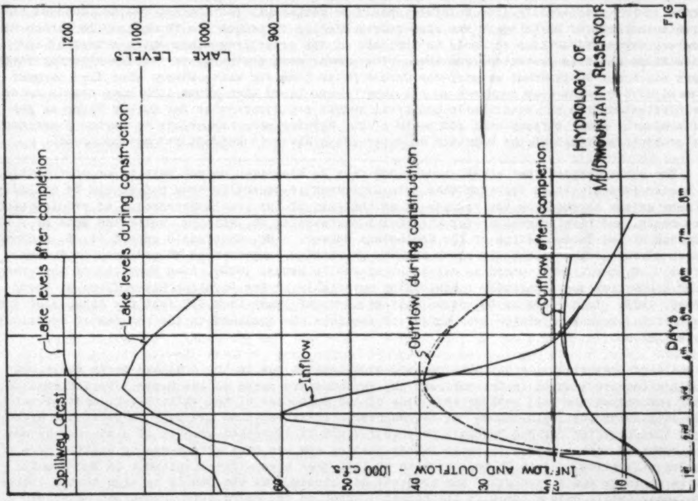
Figure 2 shows how the Reservoir would react if a flood with a maximum inflow of 60,000 cfs came during the construction-period and also after completion. Owing to the greater discharging capacity of the tunnels during construction the lake-level would only reach an altitude of 1,130 feet, but after construction the water would slightly overtop the spillway-crest at an altitude of 1,215. During construction the maximum flow in the River below the Dam would be 39,500 cfs or 65 per cent of the maximum inflow. After completion, however, the maximum outflow would only amount to 18,500 cfs or 31 per cent of the maximum inflow, and the Reservoir will really be doing its stuff.

In order to see how great a flood this Dam could stand, Figure 3 was prepared. The ordinates of the inflow-hydrograph were multiplied by three and the base correspondingly widened to obtain the inflow-pattern indicated having a maximum of 180,000 cfs. If such a flood should



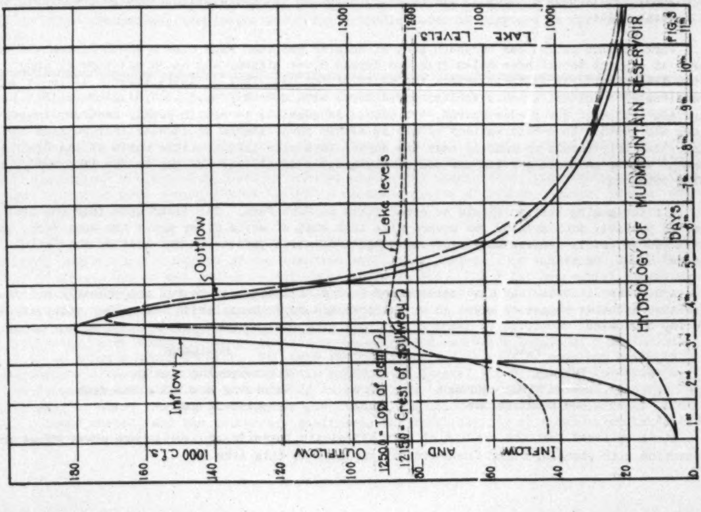
HYDROLOGY OF MUDMOUNTAIN RESERVOIR
FIG. 1

occur, waves would lap over the crest and the outflow would reach a maximum of 171,000 cfs or 95 per cent of the maximum inflow. Against such a flood, 450 cfs per square mile, the Reservoir would be practically helpless to reduce the peak. The chances of such a flood occurring are about one in a million, so we need not lie awake nights worrying over it.



HYDROLOGY OF MUDMOUNTAIN RESERVOIR

FIG. 2



HYDROLOGY OF MUDMOUNTAIN RESERVOIR

FIG. 3

F. M. VEATCH (U. S. Geological Survey, Tacoma, Washington--published with the approval of the Director, U. S. Geological Survey)--The author demonstrates that Mt. Rainier causes a reduction in precipitation over the area lying northeast of the mountain, by protecting it from the prevailing moisture-laden southwest winds. About half of the drainage-basin above Mud Mountain Dam lies in this protected area, or "rain-shadow" of Mt. Rainier. It is interesting to compare the discharge-records of the White River below Greenwater River (drainage-area 290 square miles) with those for the Carbon River near Fairfax (drainage-area 81 square miles). The time of concentration of flood-runoff from rainfall should be comparable for the two basins, because the three main forks of White River are each fairly similar in length and topography to Carbon River. However, Carbon River lies entirely in the path of the prevailing winds whereas most of the White River Basin is protected from them. The annual mean discharge per square mile for seven years was about 80 per cent greater for Carbon River than for White River. The five largest general floods which have occurred in the lower Puget Sound Area since 1932 gave nearly twice the crest-discharge per square mile and total runoff per square mile for Carbon River as for White River. Other streams west and south of Mt. Rainier were comparable to Carbon River and the protective effect of the mountain on upper White River is established beyond doubt.

The author states that areas above 6,000 feet in elevation do not make major contributions to winter floods. It is believed that this statement is generally true but should be qualified to some extent as shown by the results of an analysis of the available records of precipitation, snow-depth, and river-discharge for the basins surrounding Mt. Rainier, which was made by I. E. Anderson of the Tacoma office of the Geological Survey. Mr. Anderson's report [I. E. Anderson, Floods of Puyallup and Chehalis river-basins, Washington, unpublished MS prepared in Tacoma office U. S. Geol. Surv. under an allotment of Public Works, 1939] shows that all of the area under 8,000 feet was apparently contributing materially to the Puyallup River flood of December 10, 1933. This leads us to assume that areas up at least to 8,000 feet are capable of producing flood-runoff in winter and should, if possible, be included in the program of hydrologic investigation.

All of the meteorological stations and snow-courses now in the drainage-basin above Mud Mountain Dam are located in the northern and southeastern parts of the Basin. No information is being secured on the left bank or west side of the main stem of the White River, most of which lies outside of the "rain-shadow" of Mt. Rainier. It is believed that the value of the hydrologic investigation for Mud Mountain Reservoir could be increased greatly if a minimum of one more combined snow-course and precipitation-station and one more stream-gaging station were installed at critical points in this western or left-bank area. The investment in Mud Mountain Dam is so large and the value of the property downstream from the Dam is so high that a little more money (still only a "drop in the bucket") spent on the hydrologic investigation should be well worth while.

Park-rangers patrol the northern part of Rainier National Park once a month during the winter. At a point about three miles from the Carbon River highway and at an altitude of about 6,000 feet, their patrol-trail enters the basin of the West Fork of White River. It is thought practicable to install a small shelter-cabin here, with a weekly type recording precipitation-gage and equipment for a snow-course. It should be possible to obtain weekly recorder-inspections and monthly snow-observations by hiring either park-rangers or someone from outside the park. The trip should ordinarily take two days. This site lies a little north of the "rain-shadow" of the mountain and its use would help greatly in filling the gap in the information now being obtained.

A river-gaging station should be established on West Fork. The flood-flow from the West Fork is probably much greater per square mile than that of White River above the West Fork, and it should be fairly representative of the large area which lies north and west of the "rain-shadow" of Mt. Rainier.

Additional stations are also recommended at the following points but are probably not as important as those suggested above or as the proposed snow-course which the author mentions for Sun Top Mountain:

Place	Elevation	Equipment
Parkway	2,630	Stream-gaging station
White River entrance	3,000	Recording precipitation-gage
Mud Mountain Dam	1,310	Evaporation-pan

It is believed that the results of this hydrologic investigation will have great value in connection with planning other flood-control projects in this Area.

PROSPECTIVE DRY YEARS AND THEIR CAUSE

Halbert P. Gillette

Synopsis--Many kinds of geological phenomena clearly record important climatic cycles of different lengths, but until very recently the length of none of these cycles had been accurately determined. By means of annually deposited layers of sediment (varves) in the ocean, it has been possible to find many lengths of cycles in rock-strata, and to show that those of shorter length agree with cycle-lengths found in tree-rings and in varves in existing lakes. The author has recently completed a field-study of climatic cycles recorded in rock-strata from the northern part of the United States to the southern part of Mexico. The results of this investigation, combined with those of previous studies, are given in a Table of cycle-lengths and dates. The Table contains four important triple-progression series of cycles, all of which are harmonic. Three of the long climatic cycles are shown to have produced a downward trend in rainfall in many regions culminating in a series of droughts, beginning about 1930. This series of droughts will probably continue till about 1990, judging by the cycles responsible for it. In many regions these droughts bid fair to be more severe than any long series that has occurred in the last 20 centuries. It will therefore prove futile to continue the present policy of "relief in the dust-bowl regions." Wholesale migrations from those regions seem advisable. Weather-records kept by man go back too short a time to be of much use in forecasting climatic changes. Only climatic cycles recorded by Nature (for example, varved rock-strata, recessional moraines of glaciers, lake and marine terraces, lake and marine varves, tree-rings, etc.) can be used effectively to solve the problem of long-range forecasting. Yet neither our Weather Bureau nor that of any other nation has ever made a systematic study of these natural records of cyclic changes, and only a few scientists have done much along this line. The author presents four laws relating to cyclic phenomena, and comes to the conclusion that not only weather-cycles but many other types of radically different cyclic phenomena are concurrent effects of cyclic bombardments of the Earth by solar electrons. Among the many correlated terrestrial cycles are those of rainfall, earthquakes, magnetic storms, auroras, declination of the compass, changes of sea-level, changes of the rate of axial rotation of the Earth, and showers of meteors. Local weather-changes are, as yet, much more difficult to forecast by aid of cycles than are climatic changes over great areas. This is proven by "predicting backward," that is, by explaining past changes by the aid of cycles. The author gives an example of "predicting backward" by showing how three long cycles in his Table explain the long dry period near the close of the 18th Century. He points out that storm-tracks tend to shift to lower latitudes near maxima of rainfall-cycles, often producing opposite effects in different localities. Because all cycles are harmonic, long cycles are built up by the combined effects of short cycles, and consequently the longer the cycle the greater its amplitude. This explains why long cycles are so conspicuous in geological phenomena, a careful study of which removes any skepticism as to the probable value of long cycles for forecasting purposes.

During the last four years I have published ten papers in the Bulletin of the American Meteorological Society and in the Pan-American Geologist on climatic cycles shown in geological phenomena. Several climatic cycles of different length, but each quite constant as to length, are disclosed by: (1) Terraces around lakes and along seashores; (2) recessional moraines left by glaciers; (3) paired beds of rock of different nature; (4) sequences of rock-beds of the same nature, and similar thickness; (5) fossil zones; (6) series of coal-beds and of oil-sands; and (7) geological periods shown both by fossils and by the character of the strata. Such facts long ago converted most geologists to belief in climatic cycles of rather regular, though, until recently, unknown lengths.

The late Professor John S. Newberry of Columbia University in 1874 called attention to the strikingly similar cyclic nature of two American geological periods, now called the Ordovician and the Silurian, but he was unable to determine their length. The first successful determination of the approximate length of a geological period, or indeed of any geological cycle recorded by rock-strata, was made in 1925 by Professor L. D. Stamp. By the aid of rock-varves in Burma he estimated the duration of the Oligocene to have been of the order of 1,700,000 years. My own recent estimates, also based on varve- and strata-measurements, make the length of a geological period to be about 2,000,000 years. The term geological period is used by American geologists to designate a climatic and diastrophic cycle such as the Eocene, the Oligocene, the Miocene, and the Pliocene, which are the last four of these periods. The maximum thickness of stratified rock in each of these four periods differs too little from 13,000 feet to be accidental. Incidentally Stamp showed, and the author has confirmed, the unreliability of atomic disintegration-formulas for determining the age of rocks.

The next geological cycle whose length was found by aid of varve- and strata-measurements is to be credited to Wilmot H. Bradley of the United States Geological Survey. He found 16 pairs of beds of oil-shales and marlstone in Colorado, each pair recording a climatic cycle of about 22,000 years. According to my latest study, this cycle is about 24,300 years long, and is probably just 81 times the length of the 300-year cycle in the B-series in the accompanying Table 1. It is significant that the estimated period of its length is only six per cent less than the estimated period of the gyration of the Earth's axis. But since the estimated length of the gyratory period is based only on gravitative pull on the equatorial bulge of the Earth by Moon, Sun, and planets, it must give too long a period if solar electrons that bombard the Earth have an appreciable magnetic effect on the Earth's crust and the underlying magma. Since such electrons apparently cause the 12-hour barometric tide by inducing magnetism in the oxygen of the air, it seems to follow that solar electrons are an important factor in causing gyration of the Earth's axis. For a discussion of the correlation between this gyratory period and the glaciation cycle see articles of mine in the Bulletin American Meteorological Society [December, 1936] and Pan-American Geologist [March, 1939].

The next attempt to find the length of another climatic cycle in rock-strata by aid of varves was one that I published in the Pan-American Geologist [November, 1938]. That article deals mainly with geological and sea-level evidence of a cycle of the order of 600 years in length. Since then I have measured many more varves in rocks from the northern part of the United States to the southern part of Mexico, and have found that, on the average, their thickness is about 1/16 inch, or about 190 to the foot of rock, instead of the average of 120 per foot given in previous articles. This is in accord with Professor J. A. Udden's measurements of about 6,000 varves in a core drilled in Texas, the average being about 185 varves or years to the foot of rock; and it agrees substantially with Stamp's average of 174 per foot in Burma.

Typical series of paired beds of sandstone and shale record a climatic cycle of about 900 years. The typical thickness of such a pair is about 4.5 feet, the ordinary range being four to five feet. Often a cycle of one-third this length is recorded in this manner, by pairs of beds of different kinds of rock. More often the 300 and 100-year cycles are recorded by a series of beds of the same kind of rock in which very thin parting seams of shale sometimes separate one bed from the next. Even shorter cycles are thus recorded by a series of thin beds only about two inches thick that often look almost artificial because of the regularity of their thickness. Such thin beds often record the so-called 33-year cycle. (See Figs. 1 and 2.)

In this connection it seems well to call attention to an evident error made by Ragnar Liden in 1911. He measured nearly 6,600 thin layers of unconsolidated sediment that had been deposited beneath the sea near the mouth of the Angerman River in Sweden. These layers average about 1.5 inches thick, which is about 24 times as thick as the average annual varves in rocks of marine origin. So it is clear that they are not varves, as Liden supposed, but are layers due to short cycles. Field-studies of thin layers of rock of similar thickness (about two inches) near San Francisco, California, have shown that they simulate the appearance of varves but are not annual deposits. The physical conditions there are similar to those near the mouth of the Angerman River. In both cases a large river empties into a bay. In both cases thin layers of silicious sediment are separated by much thinner layers of argillaceous sediment. Liden inferred that these argillaceous layers correspond with the winter layer of silt found in annual varves deposited in the ancient glacial lakes of Sweden and America; but this was a mistake that would not have occurred had he made field-studies of similar layers in rocks. In consequence of this error, the rates of uplift of the land in northern Sweden were grossly overestimated, and the duration of the uplift was as grossly underestimated. This is a matter of such importance in estimating the lengths of cycles recorded by marine terraces and by uplifted delta-plains that attention is called to it in this paper, although the paper is not primarily one relating to geological problems of a cyclic nature.

It has been commonly said that varves in rocks are rare, but the contrary is the case. Although long unbroken series of varves are not common, enough varves can usually be found to determine the approximate lengths of cycles recorded by strata such as in the two types above mentioned. This is a very important and little known fact. It makes it possible for anyone to convince himself of the existence of climatic cycles of great regularity and great amplitude. For some reason rock-strata disclose this fact better than any other known type of data commonly available for study. Neither tree-rings nor lake-varves are to be compared with rock-strata as recorders of climatic cycles. I infer that at least two factors are responsible for the remarkable, but as yet seldom appreciated fact, that rock-strata record cycles so well: First, because the sediments delivered by stream- and wave-erosion are quite uniformly spread over extensive areas of sea-bed; and, second, because sea-levels change cyclicly and in harmony with climatic cycles. I infer that this latter remarkable correlation is due to cyclic influxes of solar

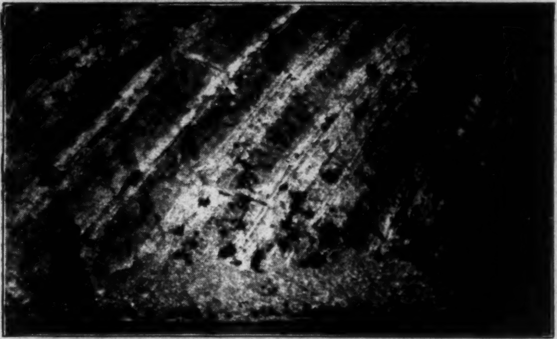


Fig. 1--Series of equally spaced beds of sandstone seperated by thicker beds of dark shale; each pair of beds records a climatic cycle

Fig. 2--Series of thin limestone beds of nearly equal thickness (each recording a cycle) underlain by another series that records a cycle three times as long

electrons that not only increase rainfall but also induce magnetism in the Earth's core. One of the effects of such an increase in magnetism is to increase the oblateness of the Earth, slightly, and thus to change the sea-level. But cyclic variations in sea-level are mainly due to numerous magnetic foci in the Earth, each of which is affected somewhat differently by any change in the influx of solar electrons into the Earth's atmosphere, and causes a somewhat different change in the elevation of the Earth's crust.

In an article on "Electron basis of diastrophism" [Pan-American Geologist, February, 1940] I discussed the evidence that all circular arcs of crustal uplift were caused by magnetic forces induced by solar electrons. It was pointed out that beneath the centers of such arc-lifts are probably magnetic poles, and that the number of these is great. On April 24, 1940, Dr. John A. Fleming, head of the Department of Terrestrial Magnetism of the Carnegie Institution, announced to the American Geophysical Union the discovery that, in addition to its main magnetic axis, the Earth has 14 secondary magnetic axes, each having about 1/80 the strength of the main field; and that many weaker fields exist. Twelve years ago I published an hypothesis of multiple magnetic fields in the Earth to explain arcs of crustal uplift, and pointed out that the same hypothesis explains the so-called "craters" of the Moon.

In recent years much has been said about tree-rings as recorders of weather and climatic cycles. Not so much, although a good deal, has been published about lake-varves as cycle-recorders. Next to nothing has been said about varved rock-strata as cycle-recorders. Yet I am convinced that this third type of Nature's record of cycles is, in most respects, the best of the

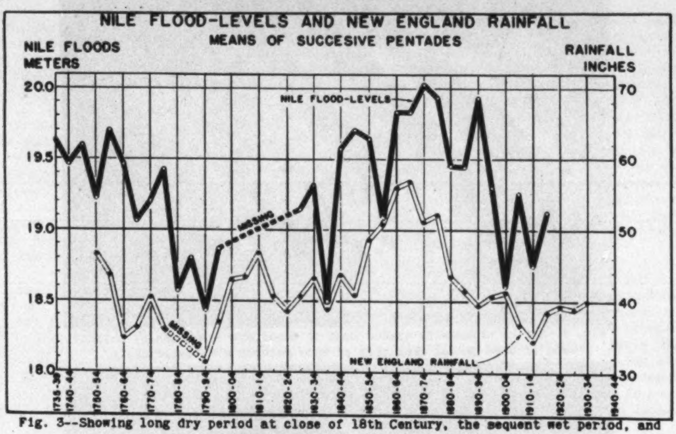


Fig. 3--Showing long dry period at close of 18th Century, the sequent wet period, and beginning of another long dry period

three. The thickness of tree-rings varies not only with rainfall but with other factors. To a less degree this is true of lake-varves, but floods often increase their thickness far more than it would be if the rainfall were less torrential. Varved rocks, however, are but slightly affected by such factors. Marine varves are remarkably uniform in thickness for long periods of time and in widely separated regions. This fits them particularly well as units by which to determine the lengths of cycles recorded either in pairs of different rock-strata or in a series of similar beds of nearly uniform thickness.

Varves in ancient glacial lakes were first put to a novel use by De Geer. He inferred correctly that a varve laid down in an ancient glacial lake reached northward as far as the front of the ice-sheet, but no farther. Hence, if the northern ends of any two varves could be located, and the intermediate varves counted, the number of years required for the ice to retreat a given distance could be determined. This makes it possible to estimate the length of a cycle recorded by a series of recessional moraines. Thus in Massachusetts, as determined by Antevs, the rate of retreat of the ice-front was about 30 years per mile, and since morainal deposits there often occur at intervals of about 3.3 miles, they record the 100-year cycle. My assurance as to that cycle is based not only upon such morainal evidence, but upon the fact that rock-strata often show a cycle of 100 years, and that tree-rings often show the same cycle.

Although De Geer, Antevs, Sauramo, and Reeds have each measured thousands of varves in ancient glacial lakes, only one man has published measurements of many varves in an existing lake! That man is Schostakowitch, a Russian. The lake is Saki, in Crimea. The period covered is 4,200 years, from 2300 B. C. to the present. This goes back 1,000 years farther than the oldest California sequoia tree-rings, first measured by Huntington and later by Douglass. I have found the Lake Saki varves of such great use in determining with accuracy the lengths and epoch-dates of many cycles that I hope that many varves in the beds of American lakes will soon be measured. Cores from such beds can be cheaply secured, probably in many regions where old trees do not exist. The dates of varves in dry lake-beds can often be determined by the aid of cycles.

The oldest rainfall-records on our Pacific Coast go back only to 1849, and only in three places. The oldest in the Mississippi Valley only to about 1836 in four places. The oldest rainfall-records on our Atlantic Coast only to 1738 in Charleston, South Carolina, but with several very long breaks. The next oldest, near Boston, goes back only to 1749, with a break during the War of the Revolution. Figure 3 shows, in condensed form by 5-year averages, the rainfall at or near Boston, as well as the flood-levels of the Nile. Tree-rings in Vermont agree well with the Boston curve of rainfall. It is obvious that man-kept records of rainfall in America are inadequate as data by which to determine either lengths or epoch-dates of long climatic cycles. Those of Europe are little better. Hence, the long-neglected, and still but scantly used records left by Nature, must be our main source of information as to climatic cycles. It is a pity that not only our Weather Bureau but that of every other country remains so apathetic toward the records of climatic cycles that Nature has kept not merely for centuries but for eons.

When I began a research on cycles 14 years ago, the main object was to find the cause of cycles. As a means to that end, I sought to find one or more empirical laws relating to cycles. It seemed likely that Nature had been no more chaotic as to weather-cycles than as to the orbital periods of planets, although laws relating to weather probably were more complex. But it certainly was not wise to agree with one critic of cycle-researchers who had said: "There are so many alleged weather-cycles that I believe in none." With equal reason might one have said the same of molecules 130 years ago, before Dalton rescued chemistry from its chaotic condition by the discovery that atoms unite in definite weights to form molecules. Prior to Kepler's discovery of his three laws, the movements of the planets seemed chaotic. Indeed the whole history of science abounds in examples showing that chaos, where it seems to exist in Nature, has been only in the seeming.

As precision in determining cycle-lengths offered the best means of finding empirical laws relating to cycles, it was decided to use the most laborious method of cycle-analysis because it was the most accurate. I mean the parallel-column method of simple averages, which in essence was devised by Balfour Stewart some 50 years ago. In order to have adequate data for application of this method of cycle-analysis, tree-rings and varves were used. But it was not till rock-strata began to be used that the first important law of cycles disclosed itself.

Having noted that geological periods or systems were usually divided by geologists into three sub-periods called lower, middle, and upper formations, and that these in turn were often divided into lower, middle, and upper members, I was led to look for other evidences of tripartite subdivisions. So many of these were found, not only in geological data but in man-kept weather-data, that I inferred the existence of a general law that may be stated thus: All cycles occur in series whose lengths are terms of a geometrical progression-series whose ratio is three.

This may be called the triple-progression law of cycle-lengths. It applies not only to the longest climatic cycles but the shortest weather-cycles. In the accompanying Table 1 are given the lengths of cycles in four triple-progression series, letter A to D; but not all the proven lengths in any series are given. There are certainly cycles much longer than those given in the B-series, for example.

The lengths of cycles were determined with increasing accuracy, until finally it became evident that all cycles are apparently harmonic. Since further investigation has confirmed this hypothesis, we have a second law, namely: All triple-progression cycles are harmonic with one another and with the Earth's orbital period.

Many cycle-researchers had found that the amplitudes (or periodic departures from a mean) of all cycle-curves are variable; but with no known law of this variability. There are changes in the amplitudes of real cycles, and the law of these changes is this: The amplitude of a cycle increases when its peaks occur at or near the peaks of a supercycle of the same triple-progression series.

This explains, at least in part, why short cycles so often rise into prominence and fade away until their effects become masked by other cycles.

Several cycle-researchers have published puzzling correlations between cycles of strikingly different types. For example, earthquakes and volcanic eruptions have been found to occur near peaks of the "eleven-year" sunspot-cycle too often to be accidental. Even comets' tails are usually more brilliant at such times, according to Pickering; and I have recently found that meteors tend to be more frequent near peaks of that cycle. Auroras long ago were found to be correlated with peaks of this cycle, leading to the inference that the Sun at such times strongly bombards the Earth with electrified particles. Correlated magnetic storms confirmed this inference. Since causes have often been discovered by correlating two or more different types of phenomena, it seemed wise to study all the published correlations relating to cyclic phenomena, and to seek to find additional correlations. There is now a sufficient body of evidence to warrant belief in a cycle-correlation law which may be expressed thus: Many (probably all) cycles of all types of terrestrial phenomena are correlated.

Since there are many types of correlated cycles that probably do not cause one another, it follows that they are probably coincident effects of a common cyclic cause. Since the most common cause of phenomena is electric in nature, it is a reasonable presumption that all cycles are correlated because they are coincidental or closely sequent effects of a cyclic emission of electric ions. The source of some of these ions is certainly the Sun. Why not of all? If so, are they predominantly negative or positive? Or are they equal in number? Facts establish preponderance of negative ions whose unit-charges are therefore electrons. The reason for this singular predominance of electrons both in the Sun and in the Earth may be due to the crushing of more protons (positive units) than electrons (negative units) by great gravitative pressure, and the liberation of radiant energy (photons). The numbers of solar electrons that bombard the Earth vary cyclicly. The consequence is a great variety of correlated cyclic phenomena, among which are rainfall, atmospheric pressure, temperature, disturbances of the Earth's crust, auroras, variations of the compass, etc., etc.

It is a singular fact that the length of the most prominent sunspot-cycle (11.11 years) differs only six per cent from the orbital period (11.86 years) of the greatest planet, Jupiter. In consequence it has often been suggested that Jupiter somehow may cause this sunspot-cycle. Perhaps this has been a putting of the cart before the horse, for Jupiter may have been generated by solar electrons carrying forth solar atoms in great abundance about every 11.11 years, mainly along the heliocentric longitude of inclination of the Sun's axis. Then any orbital matter having the same period would tend to grow in mass. Even a planet's orbital motion and axial rotation would result from the spiral influx of solar electrons around a magnetic axis. The resulting loss of solar mass would eventually tend to cause Jupiter to move out farther from the Sun, thus lengthening its period. Other factors, such as friction, would tend in an opposite way, thus explaining why all planet-periods have not been lengthened in the same degree. Table 1 seems to support this theory. Incidentally this explains why several researchers have erroneously attributed certain weather-cycles to planetary causes.

It has always been very puzzling that although the sunspot-cycle of 11.11 years is very conspicuous, the corresponding weather-cycle is not. As a tentative explanation of this anomaly the following is offered: If the Sun has a core that rotates in 11.11 years, then its magnetic axis must be most inclined every 11.11 years toward streams of electrons from the center of the Galaxy. More electrons spiral toward the Sun's south magnetic pole, and upon entering the Sun cause more rotating sunspots in that hemisphere than in the northern hemisphere. As a matter of fact sunspots are usually much more numerous in the southern hemisphere. This would give prominence to a sunspot-cycle of 11.11 years, but there would not necessarily be a prominent weather-cycle of that length, for the latter is caused by an efflux of solar electrons that reach the Earth. Incidentally, this prominence of "the eleven-year" spot-cycle has led many researchers to make vain efforts to find simple harmonic relations between that cycle and all other cycles. It is harmonic with other cycles, but not in as simple a manner as had been supposed.

Study of long cycles in Table 1 of cycle-lengths shows that they will produce minimum rainfall as follows:

A 243-year cycle in 1966
B 100-year cycle in 1955
C 165-year cycle in 1960
D 89-year cycle in 1943

For comparison as to the causes of the long drought at the close of the 18th Century, we have maximum dryness caused as follows:

A 81-year cycle in 1803
B 100-year cycle in 1755
C 165-year cycle in 1796
D 267-year cycle in 1765

Of these cycles the one with the greatest amplitude is the 100-year cycle, which did not assist in causing the drought at the close of the 18th Century, but is a very important factor in the drought now in progress. Hence the prospective drought will probably exceed in duration and in intensity that of about 145 years ago. That this is likely to be the case is also shown by the record-breaking series of droughts that began 12 years ago, following a long decline in rainfall that began about 1870.

If the next climax of dryness occurs about 1960, as is probable, it will mark the end of a 30-year period of severely declining rainfall in many regions. Another 30 years of extreme dryness, relieved only by short, wet spells, will have to elapse after the climax of 1960, before conditions will again be what they were prior to the great drought of 1930. Hence some 60 years of recurring severe droughts may be expected. Only ten of those 60 years are behind us. The longest famine-period recorded in history is one that lasted 72 years in China. So we are not facing an entirely unprecedented situation, although it bids fair to be the most prolonged period of recurring droughts in historical times.

Several hundred millions of dollars have already been spent for relief in the "dust-bowls" of our Great Plains. Well meaning though this expenditure has been, it has acted merely as a

palliative, for another 50 years of worse conditions lie ahead. Conviction as to a dire outlook for the next half-century probably will force itself upon any intelligent man who will study thoroughly Nature's records of cyclic phenomena.

Table 1--Lengths and dates of four series of triple-progression cycles

Unit	A	B	C	D
Days	4.51	5.57	3.05	4.93
	13.53	16.71	9.16	14.81
	40.58	50.10	27.49	44.43
Months	4.00	4.94	2.71	4.40
	12.00	14.82	8.13	13.19
	36.00	44.44	24.39	39.56
Years	9.00	11.11	6.10	9.89
	27.00	33.33	18.29	29.67
	81.00	100.00	54.87	89.01
	243.00	300.00	164.62	267.03
Date max.	1845.18	1905.18	1878.35	1898.58
Date min.	1723.68	1755.18	1796.04	1765.06

Footnote: The dates of maxima and minima of rainfall at the bottom of each column apply to every cycle in that column. Weather-cycles often invert their phase. This often produces an apparent cycle of half the length given in this Table. Sunspot-cycles rarely invert their phase. The same is true of long climatic cycles in a given region. Maximum rainfall is associated with minimum temperature in climatic cycles.

If such natural records are as valuable as alleged, it will be asked why they have not been utilized long ago. A full answer to that question cannot be given until someone makes a thorough research to find the answer to a broader question: Why have the observational sciences progressed so little compared with the experimental sciences? In the latter group many unifying laws of great practical value have been found, whereas in the former group the number of such laws is relatively few.

Meteorology has always had for its great goal the ability to forecast weather far ahead. Our Weather Bureau makes forecasts only a few days ahead, thus conceding the slowness of progress in gaining knowledge about weather. One reason for such slowness is found in the indifference with which several great discoveries have been treated. For example, it was more than four centuries ago that Leonardo Da Vinci discovered that annual tree-rings recorded changes in annual rainfall in Italy. Yet no weather bureau of any nation has followed up this important discovery by systematically measuring and studying tree-rings. About 40 years ago, a comprehensive tree-ring research was begun by a professor of astronomy, A. E. Douglass, who still has but few followers in this important meteorological field.

More than 170 years ago a Swedish scientist pointed out that thin layers of silt in ancient lake-beds were probably annual deposits, or varves as they are now termed. If so, they would obviously be thicker when rainfall was heavier, and thinner when it was lighter; yet not a single weather bureau has systematically followed up this important discovery. It remained for a Swedish professor of geology, Baron Gerard De Geer, to begin such an investigation about 35 years ago, and he, too, has had few followers.

It would seem that nothing could be more obvious than that reliable long-range forecasting can be effected only through knowledge of long cycles, and that adequate knowledge of these is not attainable merely by studying weather-records that man has kept for a century or two at best. The only pathways to adequate knowledge about long climatic cycles are via the varve and the tree-ring; pathways that as yet show the footprints of only an occasional lone traveler in search of laws that give unity to numerous facts, and causes that give meaning to the laws.

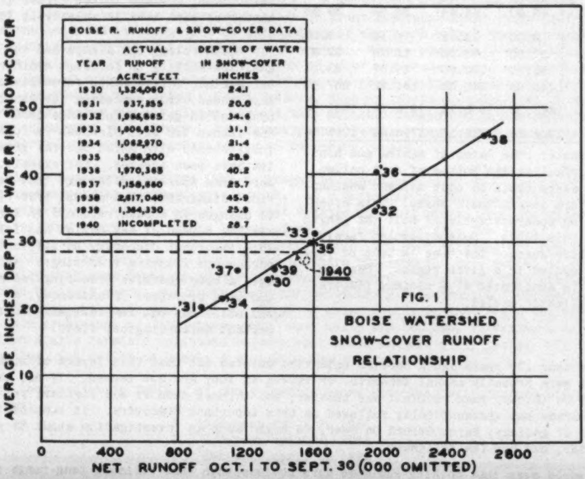
1125 Oak Grove Avenue,
San Marino, California

MEASUREMENT OF FOOTHILL-SPRINGS TO DETERMINE SOIL-MOISTURE AND GROUND-WATER CONDITIONS IN SNAKE BASIN, IDAHO

James C. Marr

Need for an index to dryness of watershed--To forecast runoff from snow-cover closely every year it appears necessary that watersheds be normally wet each spring, or that the proper allowance be made for dryness of the earth-mantle. Theoretically, water-supply forecasting based on snow-surveys presupposes a close relationship exists between the amount of water stored as snow in the mountains at the end of winter and the runoff that occurs during the succeeding spring and summer months. This is notably the case in western United States, except occasionally when abnormal conditions occur, such as excessive dryness of watershed. Obviously, when the earth-mantle is very dry, an inordinate amount of the water from melting snow may be withheld on watersheds to replenish the soil-moisture and ground-water. At such times the runoff, compared to the mountain snow-cover, will be smaller. The water-supply forecaster is bothered to know how much smaller, because he does not have satisfactory ground-water records from which to determine the correction accurately.

The problem is well illustrated by the plotted comparison of snow-cover and runoff for Boise River Drainage, Idaho, for the years 1930 to 1939, inclusive (Fig. 1). Here the average depth of water in inches found in the snow-cover on three snow-courses is plotted as the ordinate, and the runoff as the abscissa. It will be seen that the runoff, compared to the water in the snow-cover, was disappointing both in 1936 and 1937. The preceding falls and winters of these two years were characterized by unusual dryness of earth-mantle on this watershed, brought about by below-normal temperatures and low precipitation as rainfall as compared to that which occurred as snow.



BOISE R. RUNOFF & SNOW-COVER DATA

YEAR	ACTUAL RUNOFF ACRE-FEET	DEPTH OF WATER IN SNOW-COVER INCHES
1930	1,324,060	24.1
1931	937,255	20.0
1932	1,986,865	34.6
1933	1,606,630	31.1
1934	1,062,970	21.4
1935	1,588,200	29.9
1936	1,970,365	40.2
1937	1,158,660	25.7
1938	2,617,040	45.9
1939	1,384,330	25.8
1940	INCOMPLETED	28.7

FIG. 1

BOISE WATERSHED SNOW-COVER RUNOFF RELATIONSHIP

Fig. 2--Small. well-developed underground spring

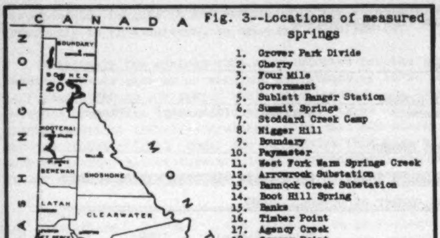

CANADA
WASHINGTON
OREGON
NEVADA
UTAH
WYOMING
MONTANA
IDAHO
YELLOWSTONE NATIONAL PARK
BOUNDARY
BONNER
KOOTENAI
BENEWAH
SHOSHONE
LATAH
CLEARWATER
NEZ PERCE
LEWIS
ADAMS
VALLEY
WASHINGTON
PAYETTE
GEM
BOISE
CANYON
ADA
ELMORE
CAMAS
BLAINE
CUSTER
LEMHI
CLARK
FREMONT
JEFFERSON
MADISON
TETON
BUTTE
BONNEVILLE
BINGHAM
LINCOLN
GOODING
JEROME
MINIDOKA
TWIN FALLS
OWYHEE
CASSIA
POWER
BANNOCK
CARIBOU
ONEIDA
FRANKLIN
BEAR LAKE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Fig. 3--Locations of measured springs

1. Grover Park Divide
2. Cherry
3. Four Mile
4. Government
5. Sublett Ranger Station
6. Summit Springs
7. Stoddard Creek Camp
8. Nigger Hill
9. Boundary
10. Paymaster
11. West Fork Warm Springs Creek
12. Arrowrock Substation
13. Bannock Creek Substation
14. Boot Hill Spring
15. Banks
16. Timber Point
17. Agency Creek
18. Cougar Point
19. Dougherty
20. Upper Benton

Choice of a record--It has been suggested, that when unusual drought occurs, records that precisely reflect the relative dryness of watersheds may serve as reliable bases for properly modifying the snow-survey results. The flows of a selected number of underground foothill-springs are being measured in Idaho, particularly in Snake Basin, to provide such a record. Flow-measurements of springs rather than other indicators of depleted soil-moisture and ground-water are prescribed in this particular case for the following reasons:

Mere general knowledge that the soil is dry beneath the snow-pack, that lake- and pond-levels are low, and that the flow of streams is less than usual--the supplemental information in this respect that snow-surveyors are instructed to give under remarks in their field-notes--serves as a warning that the runoff from the snow-cover will be disappointing, but provides no means for judging how much the snow-cover should be discounted.

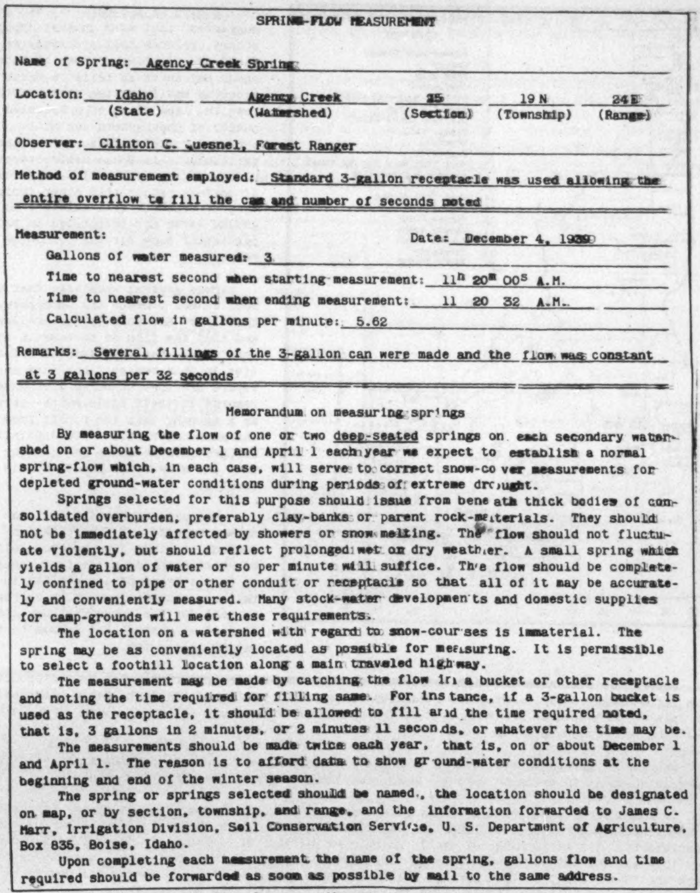
The use, along with the snow-survey results, of precipitation-records or river-flow records, either of which being of sufficient duration to permit proof of its utility in this connection, frequently corrects in part for the occasional dry condition of watershed, but seldom to the extent called for.

Records of soil-moisture might serve the purpose, but their procurement has been discouraged thus far because of the seeming unsuitability of the earth-mantle of the Snake Basin watersheds, the lack of an adaptable procedure for soil-sampling to follow, and the labor, time, and facilities required to obtain them.

Records of ground-water levels also might serve, but the expense of providing satisfactory observation-wells in which to make the measurement has prevented getting these under way.

In comparison, the spring-flow record appears to be as promising an index as any to dryness on Snake Basin watersheds. Besides, little difficulty or expense is involved in procuring the measurements. The performance of small underground springs in foothill-regions during the drought year 1934 and the intensive work done at that time to keep them from drying up, is taken as evidence that the flow of certain springs may be depended upon to reflect properly the degree of dryness that must be taken into account in forecasting runoff from snow-cover.

Facilities that appear ideal for the purpose are available for trying out the plan. Particularly on the public domain and in the foothill portions of national forests, where there is less abundance of water than in the high mountains, many small springs have been developed on camp-ground sites and as watering places for range-stock. Some of these are deep-seated in clay, shale, or rock and yield, as a consequence, streams that are little influenced by surface-inflow. In such cases the discharge is usually completely confined within a conduit, as illustrated in Figure 2, which makes its measurement a simple and accurate operation. Furthermore, these springs are frequently located along beaten paths of travel, and in at least partially settled country where they are readily accessible.



SPRING-FLOW MEASUREMENT

Name of Spring: Agency Creek Spring

Location: Idaho (State) Agency Creek (Watershed) 25 (Section) 19 N (Township) 24 E (Range)

Observer: Clinton C. Quesnel, Forest Ranger

Method of measurement employed: Standard 3-gallon receptacle was used allowing the entire overflow to fill the can and number of seconds noted

Measurement:

Date: December 4, 1939

Gallons of water measured: 3

Time to nearest second when starting measurement: $11^h\ 20^m\ 00^s$ A.M.

Time to nearest second when ending measurement: 11 20 32 A.M.

Calculated flow in gallons per minute: 5.62

Remarks: Several fillings of the 3-gallon can were made and the flow was constant at 3 gallons per 32 seconds

Memorandum on measuring springs

By measuring the flow of one or two deep-seated springs on each secondary watershed on or about December 1 and April 1 each year we expect to establish a normal spring-flow which, in each case, will serve to correct snow-cover measurements for depleted ground-water conditions during periods of extreme drought.

Springs selected for this purpose should issue from beneath thick bodies of consolidated overburden, preferably clay-banks or parent rock-materials. They should not be immediately affected by showers or snow melting. The flow should not fluctuate violently, but should reflect prolonged wet or dry weather. A small spring which yields a gallon of water or so per minute will suffice. The flow should be completely confined to pipe or other conduit or receptacle so that all of it may be accurately and conveniently measured. Many stock-water developments and domestic supplies for camp-grounds will meet these requirements.

The location on a watershed with regard to snow-courses is immaterial. The spring may be as conveniently located as possible for measuring. It is permissible to select a foothill location along a main traveled highway.

The measurement may be made by catching the flow in a bucket or other receptacle and noting the time required for filling same. For instance, if a 3-gallon bucket is used as the receptacle, it should be allowed to fill and the time required noted, that is, 3 gallons in 2 minutes, or 2 minutes 11 seconds, or whatever the time may be.

The measurements should be made twice each year, that is, on or about December 1 and April 1. The reason is to afford data to show ground-water conditions at the beginning and end of the winter season.

The spring or springs selected should be named, the location should be designated on map, or by section, township, and range, and the information forwarded to James C. Marr, Irrigation Division, Soil Conservation Service, U. S. Department of Agriculture, Box 835, Boise, Idaho.

Upon completing each measurement the name of the spring, gallons flow and time required should be forwarded as soon as possible by mail to the same address.

Fig. 4--Form for recording spring-flow measurement

Ordinarily all that is required in the way of equipment for making the measurement is a bucket or other receptacle of known capacity and a watch, preferably a stop-watch. The task is one that may be performed satisfactorily by any interested, careful cooperator, and the time and labor required is such that it may usually be arranged for on a voluntary basis.

Procedure--It was considered expedient to begin with a restricted program that, admittedly, may not prove adequate. Measurements were begun more or less experimentally last fall with foreknowledge that some of the springs selected for the purpose might prove unsuitable, that the prescribed time-schedule for making the measurements might prove faulty, and that the program might need enlargement. Furthermore, the program was intentionally restricted to probable minimum requirements, because it was necessary to ask voluntary cooperators, who already contributed generously to snow-surveys, to make the measurements.

Relatively few springs (20) were selected for the purpose (Fig. 3). In all instances the selections were made by or with the assistance of local authorities who knew something about the performance of the springs in their neighborhood. To ascertain if there was agreement in performance of springs located close together, three or four are grouped, in several cases, on a single important tributary drainage. The rest are widely scattered, more or less uniformly, through southern Idaho, under the assumption that they might suffice for large, perhaps overlapping areas. All of them are located in foothill-regions where water is scarce during the summer months and considerable excavation is required to develop a satisfactory spring.

Only two yearly measurements for each spring were called for. December 1 and April 1 were the dates fixed. December 1 was judged to be approximately the best time of the year to appraise the effects of fall precipitation on ground-water conditions. According to a statistical analysis that was made of the effects of fall precipitation [James C. Marr, Symposium on effect of soil-priming by fall precipitation on spring runoff, Upper Snake Basin, National Research Council, Trans. Amer. Geophys. Union, 1939, pp. 106-109, 1939], freezing temperatures which prevail in the foothill-regions after December 1 tend to minimize until spring further increase in the supply of ground-water. On the other hand, it appeared that precipitation as rain on the unfrozen ground, or dry weather which is apt to occur in the fall prior to December 1, might change ground-water conditions materially.

The April 1 measurement was prescribed for two reasons. It was believed that the flow of a suitable spring either would increase moderately at this time of the year or would remain approximately the same as at the beginning of winter. The increase might indicate ground-water conditions favorable to a normal runoff from the snow-cover, whereas the same flow as that of a preceding dry fall, might indicate a disappointing runoff. The second reason for the measurement of April 1 was to show whether or not the springs selected would be satisfactory. In case the increased flow on April 1 proved excessive it might indicate a too great effect from surface-inflow.

Forms for recording the measurements, to which were attached full instructions and explanations for selecting and measuring the springs, were supplied to the cooperators who made the measurements. Figure 4 is a facsimile of one of these forms upon which a measurement has been recorded.

The procedure that may be followed for statistical analysis of the spring-flow data several years hence is fairly well defined and it will be simple if the spring-flow records measure up to expectation. The measurements must first be carried through one year similar to 1937 on the Boise River watershed (Fig. 1). The percentage-change in spring-flow from the normal, or from the maximum may then be reduced to constants which, when multiplied by the average inches of depth of water in the snow-cover, will discount the snow-water in exactly the amount to make the relationship of snow-cover to runoff correspond with that of ordinary years. In other words, the plotted point for 1937 in Figure 1 would thus be lowered to correspond with those for 1938, 1935, and 1931. When it becomes possible to apply this correction-constant successfully a second year when the ground-water is deficient, it will be sufficiently proved to begin using it in water-supply forecasting.

Discussion of results--Examination of the one year's records of spring-flow is more enlightening than might be expected. The fall of 1939 and the winter of 1940 proved to be an excellent period for starting these records since it was possible to observe the effect of a dry fall and a warm, wet winter on ground-water conditions.

The precipitation last summer and fall throughout Snake Basin was unusually light (Table 1). By January 1, 1940, river-stages had dropped to record low levels and their watersheds had become exceedingly dry, At this time it appeared certain that the April 1, 1940, snow-survey data would have to be discounted in estimating the probable runoff from snow-cover. Between January 1, 1940, and April 1, 1940, however, an unprecedented change in this condition took place. During the winter, when normally there is little or no increase of soil-moisture or ground-water in the mountains, precipitation as rain or wet snow and abnormally high temperatures (Table 1) resulted in well-soaked watersheds before spring. When the water-supply forecasts were made this spring (April 1, 1940) they were based on the snow-survey data alone, it being considered unnecessary to take into account the dry fall of 1939. The runoff indicated for Boise River in Figure 1 was the amount predicted--1,500,000 to 1,550,000 acre-feet.

Table 1--Climatological data for southern Idaho, 1939-40

Date	Accumulated			
	Precipitation from October 1, 1939, to date, per cent of normal		Temperature-departure from normal from January 1, 1940, to date, °F	
	Southwest Idaho	Southeast Idaho	Southwest Idaho	Southeast Idaho
December 31, 1939	60	52	.....	.....
January 31, 1940	92	90	+ 3.2	+ 2.1
February 29, 1940	117	93	+ 7.3	+ 7.8
March 31, 1940	95	108	+11.0	+12.7

Table 2 shows how the dry fall and wet, warm winter affected the flow of the springs that were measured. Of the 16 measured both in the fall and spring, the flow of six increased from fall to spring by 86 to 216 per cent, of five by 23 to 67 per cent, and of two by 4 to 5 per cent. The remaining three decreased in flow. Though some of these measurements, particularly the latter three, seem irrational and both the locations and the methods of measurement will be further scrutinized, there are no grounds for concluding that any of the springs were carelessly selected or that the measurements are in error. There is good assurance that all of these springs are of the underground type and that the men who made the measurements did so with care.

Table 2--Spring-flow record, 1939-40

Name of spring	Drainage	Cooperator supplying measurement	Discharge-measurements, gallons per minute[1]				Per cent increase from Dec.1,1939,to April 1, 1940
			Oct. 1939	Dec. 1939	April 1940	May 1940	
		Southern Idaho					
Grover Park Divide	Salt River	Wyoming National Forest	....	1.07	....	25.00	....
Cherry	Portneuf River	Caribou National Forest	....	3.63	4.02	.....	+111
Four Mile	Trout Creek	Minidoka National Forest	....	1.33	3.53	.....	+165
Government	Albion Mt.	Minidoka National Forest	....	15.62	2.85	6.00	- 82
Sublett River Station	Sublett Creek	Minidoka National Forest	....	60.00	75.00	.....	+ 25
Summit Springs	Sublett Creek	Minidoka National Forest	....	0.86	1.60	.....	+ 86
Stoddard Creek Camp	Mud Lake	Targhee National Forest	....	3.80	4.00	.....	+ 5
Nigger Hill	Big Lost River	Challis National Forest	....	16.36	13.85	.....	- 16
Boundary	Wood River	Sawtooth National Forest	....	3.16[2]	10.00	.....	+216
Paymaster	Wood River	Sawtooth National Forest	....	30.00	50.00[3]	.....	+ 67
W. Fork Warm Spring Creek	Wood River	Sawtooth National Forest	....	2.50[2]	3.53	.....	+ 42
Arrowrock Substation	Boise River	Intermountain Forest and Range Experiment Sta.	....	0.32	1.03	0.86	+216
Bannock Creek Substation	Boise River	Intermountain Forest and Range Experiment Sta.	1.45	1.58	4.50	.....	+185
Boot Hill Spring	Boise River	Intermountain Forest and Range Experiment Sta.	....	0.71	0.87	.....	+ 23
Banks	Payette River	Payette National Forest	....	....	1.76	.....	....
Timber Point	Payette River	Payette National Forest	....	....	40.00	40.00	....
Agency Creek	Salmon River	Salmon National Forest	....	5.62	8.18	.....	+ 46
Cougar Point	Salmon River	Salmon National Forest	....	2.75	2.00	.....	- 9
Dougherty	Salmon River	Challis National Forest	....	42.50	44.00	.....	+ 4
		Northern Idaho					
Upper Benton	Clark Fork	Northern Rocky Mountain Forest and Range Experiment Station	....	4.50	9.00	60.00	+100

[1] Measurement made approximately on the first of the month unless otherwise noted. [2] Measurement made during November. [3] Measurement made April 25.

Among the springs from which the flow increased the most are some that have all appearances of being most ideal for estimating purposes. Their performance is weighted heavily as evidence that a near maximum accretion of soil-moisture and ground-water actually occurred during the winter of 1940. For the final proof, the runoff from snow-cover for such streams as Boise River, for which the relationship is well established, may be studied. The evidences now are that ground-water conditions can improve during the winter. Successful determination of the watershed dryness-factor through use of spring-flow records, appears to require, therefore, that the springs be measured at the end of winter as a check on their measurement during the preceding fall.

It is quite probable that 11 of the 16 springs may have equaled their maximum flow at the time they were measured in April, 1940, and hence may have shown the soil-moisture and ground-water to be at capacity-peak. Even the two that increased four or five per cent may have indicated the same thing, but this is unlikely. In other words, increases in flow all the way from 23 to 216 per cent may mean that the 11 springs had reached their maximum rate of flows. Obviously, this maximum, or the departure therefrom, is needed to interpret properly spring-flow measurements in terms of ground-water conditions. To this end and to learn as much as possible about the performance of the springs they should be measured monthly for a year or more.

Undoubtedly the three springs that decreased in flow from fall to spring are unsuitable for our purpose if the inference that this is their regular performance is correct. Lacking proof to the contrary, it might be assumed that the flow of these springs failed to increase due to their slow response to the improved ground-water conditions. Such a possibility might be worth considering when selecting springs. Monthly measurements might be further justified as a means for quickly eliminating springs that are unsatisfactory in this respect.

Plans to make the spring-measurement program for Snake Basin conform with these findings are being considered and will be put into effect as far as possible this summer.

Division of Irrigation, Soil Conservation Service,
U. S. Department of Agriculture,
Boise, Idaho

DISCUSSION

J. E. CHURCH (University of Nevada, Reno, Nevada)--Since springs are usually deep-seated and fail only after a succession of dry seasons, their flow should be considered an index of the preceding seasons rather than a measure of the soil-moisture of the present. Furthermore, the springs frequently lie below the snow-fields for which an index is sought.

The problem is highly commendable but should also be approached from the comparison of cumulative snow-cover for brief cycles with the present trend of the flow of adjoining springs. The greatest difficulty will probably be the measurement of the flow of the latter. Such has been the case with Steamboat Springs near Reno where measurements of snow-cover for more than a quarter-century are available.

In case discharge-measurements of the artesian flow near the base of Charleston Peak, southern Nevada, are still maintained, snow-survey courses will be established on this Peak (elevation 10,874 feet) under the direction of Jack J. McNutt, Forester, United States Forest Service, who was earlier engaged in snow-surveying and snow-research in Yellowstone National Park.

Since the snow-cover is far more efficient than the same amount of rain, especially if intermittent, measurements of the former should preferably form the basis of any study of spring- or stream-flow.

REVISED PROCEDURE FOR FORECASTING THE SPRING RUNOFF ABOVE FORT PECK

D. B. Freeman

(The opinions expressed are those of the author, and do not necessarily reflect the official views of the United States Engineer Department.)

Inauguration of snow-surveys for drainage-area above Fort Peck

(1) In 1934, fifteen snow-survey courses were established in Montana in the upper Missouri headwaters-region for use in forecasting the spring runoff above Fort Peck. Beginning in 1935, predictions were made each year of the runoff for April to July, inclusive, based on snow-surveys at these established courses. The field-work has been done by personnel of, and under the direc-

tion of, the District Engineer of the United States Geological Survey at Helena, Montana, for the Division Office, United States Engineer Office at Kansas City, Missouri, with funds provided by the War Department. The courses are all located in the headwaters-region above Fort Peck, at elevations varying from 5,250 to 8,450 feet above mean sea-level. The most northerly course is located at Marias Pass and the most southerly course at West Yellowstone. The weighted mean water-depth of the snow at these stations appears to fairly accurately represent the mean water-content of the snow for the headwaters-region.

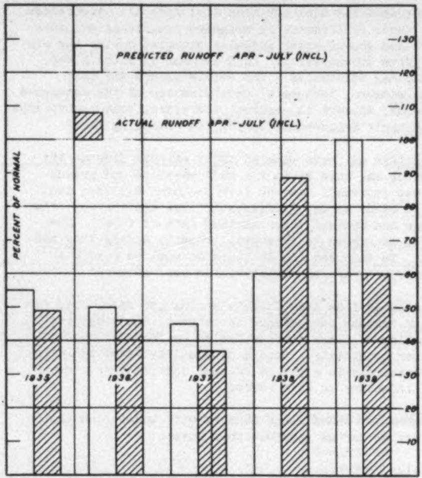


FIG. 1 — ACTUAL AND PREDICTED RUNOFF ABOVE FORT PECK FOR PERIOD APRIL TO JULY (INCLUSIVE)

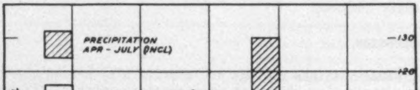


FIG. 2 — ACTUAL RUNOFF AND PRECIPITATION ABOVE FORT PECK FOR PERIOD APRIL TO JULY (INCLUSIVE)

Accuracy of predictions of runoff above Fort Peck to date

(2) The predicted runoff for April to July, inclusive, for each of the years 1935, 1936, and 1937, differed little from the actual runoff. The greatest difference was in 1937, when the predicted runoff was 45 per cent of "normal," and the actual runoff was 37 per cent of "normal" (see Fig. 1). During these three years of successful predictions, the spring precipitation was considerably below "normal" (see Fig. 2) and the runoff from snow-melt constituted a relatively large part of the combined runoff from snow-melt and precipitation.

(3) The predicted runoff for April to July, inclusive, for 1938 and 1939 differed considerably from the actual runoff. The prediction for 1938 was for a 60 per cent of "normal" runoff, whereas the actual runoff was 89 per cent of "normal;" the prediction for 1939 was for a "normal" runoff, whereas the actual runoff was only 60 per cent of "normal" (see Fig. 1). In each case the predictions were based on the same method previously employed in making the forecasts for 1935, 1936, and 1937.

(4) The inaccuracy of the predictions for 1938 and 1939 was due primarily to the large difference between the anticipated and actual precipitation during the runoff-period. In 1938 the precipitation was expected to be below "normal," and actually it was 130 per cent of "normal"; in 1939 the precipitation was expected to be above "normal," and it was only 88 per cent of "normal" (see Fig. 2).

Inherent difficulties in forecasting runoff for areas east of the Continental Divide

(5) An analysis of hydrological data for areas east and west of the Continental Divide shows a sharp contrast between the two areas as regards the amount of precipitation which occurs in the

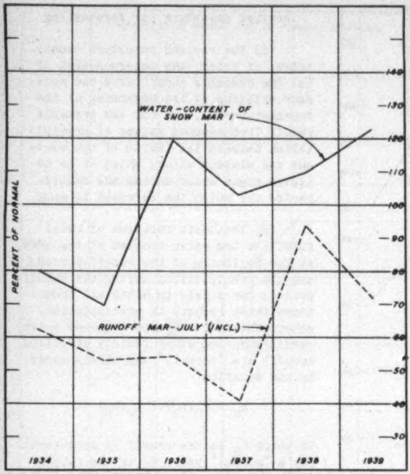


FIG. 3 — WATER-CONTENT OF SNOW ON MARCH 1 AND ACTUAL RUNOFF ABOVE FORT PECK FOR PERIOD MARCH TO JULY (INCLUSIVE)

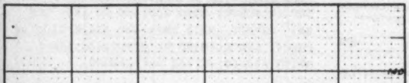


FIG. 4. - ACTUAL RUNOFF AND PRECIPITATION FOR PERIOD MARCH TO JULY (INCLUSIVE)

form of snow preceding the spring runoff-period and the amount of precipitation which occurs as rain during the spring runoff-period. For example, in the drainage-area above Fort Peck, the "normal" precipitation during the period November to February, inclusive (which is composed largely of snow), is only about one-third as great as the "normal" precipitation during the period March to July, inclusive (which is composed largely of rain). A similar relationship exists in other areas east of and contiguous to the Continental Divide. By way of contrast, in Oregon west of the Cascade Mountains, the "normal" precipitation during the period November to February, inclusive, is about twice as great as the "normal" precipitation during the period March to July, inclusive. In some areas west of the Continental Divide the ratio is less than this, but in general is greater than one.

(6) From these comparisons it is seen that, for the drainage-area above Fort Peck, the precipitation which occurs during the snowfall-period, and on which the water-content of the snowpack at the beginning of the spring runoff-period depends, is ordinarily so much less than the precipitation which occurs during the spring runoff-period that forecasts of runoff based on snow-surveys alone would necessarily be subject to large errors unless the amount of the spring precipitation which would occur could be determined in advance.

(7) Figure 3 shows the weighted mean water-content of the snow at the 15 snow-courses for each of the years 1934 to 1939, inclusive, on March 1, and the actual runoff for each of these same years for the period March to July, inclusive. Obviously there exists little correlation between these values. Figure 4 shows values of total precipitation during the months of March to July, inclusive, and the corresponding actual runoff. There exists, in this case, a fairly well-defined correlation between these values. Figure 5 shows the combined total values of the water-content of the snow at the 15 snow-courses (weighted to represent an average depth of water over the entire basin) and the average actual precipitation over the basin for the period March to July, inclusive. There exists an even better correlation between these values. A detailed study of the data used in making up these curves suggested the revised procedure for forecasting which was used in 1940 for the first time.

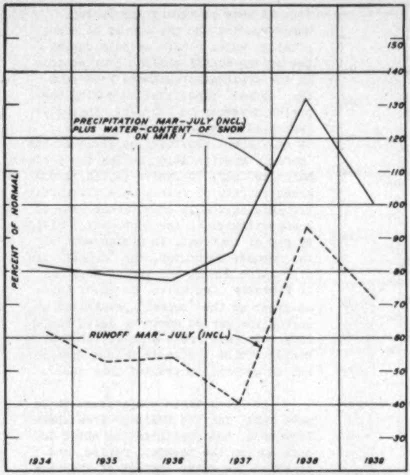


FIG. 5 - ACTUAL RUNOFF AND COMBINED PRECIPITATION PLUS WATER-CONTENT OF SNOW ABOVE FORT PECK FOR PERIOD MARCH TO JULY (INCLUSIVE)

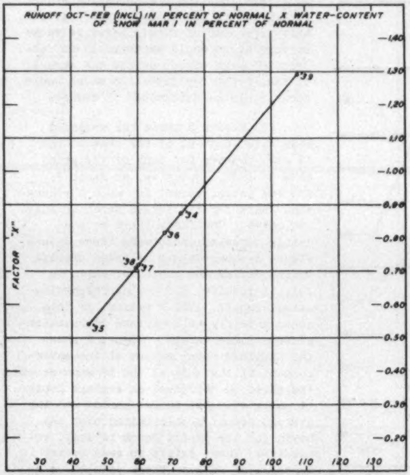


FIG. 6 - VALUES OF FACTOR "X" IN GENERAL EQUATION

Revised procedure for forecasting

(8) The revised procedure constitutes, in brief, the determination of (a) the probable runoff from the snow-pack existing at the beginning of the forecast-period, and (b) the probable runoff from assumed values of precipitation between the limits of the maximum and minimum values which it is believed might occur during the runoff-period for which the forecast is made.

(9) The basic relation of total runoff to the water-content of the snow at the beginning of the runoff-period and the precipitation during the runoff-period, for a year in which all conditions (with respect to precipitation, water-content of the snow, ground-water conditions, and other factors affecting runoff) are "normal," may be expressed by the equation

$$R_N = K_S(R_N) + K_P(R_N)$$

in which R_N is the runoff in acre-feet for a "normal" year, K_S is the factor which, when applied to the "normal" runoff, will show the proportion of runoff contributed by snow-melt, and K_P is the factor which, when applied to the "normal" runoff, will show the proportion of runoff contributed by precipitation which occurs during the period.

(10) For years in which one or more of the factors affecting runoff are not "normal," the proportions contributed by snow and rain will vary. Under these conditions the probable runoff may be determined from a modification of the basic relation by the inclusion of two variable factors, X and Y.

General equation of runoff

(11) The general equation of runoff, when one or more of the factors affecting the runoff are not "normal," may be expressed by the equation

$$R = (K_SR_N)(X) + (K_PR_N)(Y)$$

where R is the total runoff in acre-feet for the period desired; X is a variable factor for determining the probable runoff from the snow-pack at the beginning of the period, which is related to and dependent upon (a) water-content of the snow-pack at the beginning of the period and (b) runoff-trend for a selected period immediately preceding the beginning of the runoff-period; and Y is a variable factor for determining the probable runoff from precipitation during the period, which is related to and dependent upon (a) the actual precipitation which will obtain during the period and (b) the relation

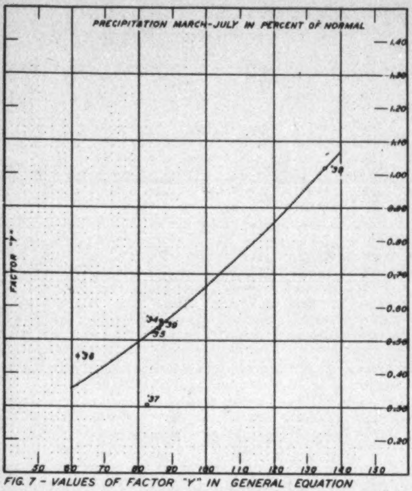


FIG. 7 - VALUES OF FACTOR "Y" IN GENERAL EQUATION

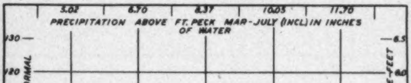


FIG. 8 - PREDICTED VALUES OF RUNOFF ABOVE FORT PECK FOR PERIOD MARCH TO JULY (INCLUSIVE) 1940

of the amount of runoff which will obtain during the period to the total precipitation which occurs during the period.

(12) Previous to 1940, the initial forecasts were made for the period April to July, inclusive, only. However, in 1940, immediately following the March 1 snow-surveys, an initial forecast was made for the period March to July, inclusive. Detail analysis indicates that for the period March to July, inclusive, the "normal" runoff, R_N, is equal to approximately 5,000,000 acre-feet, the factor K_S is equal to approximately 1/4, and the factor K_P is equal to approxi-3/4. Therefore, the general equation for determining the runoff for the period March to July, inclusive, may be expressed in the simplified form

$$R = 1,250,000(X) + 3,750,000(Y)$$

Determination of factor X in general equation

(13) The amount of runoff which will obtain from the melting of the snow-pack existing on March 1 will depend to a large extent upon conditions of soil and ground-water prior to the runoff-period. These and other factors affecting the amount of water in the snow-pack which will appear as runoff will be reflected in the trend of runoff prior to March 1.

(14) For conditions approximating those which have obtained during the past few years, it appears that the proper value of X to be used in the equation may be evaluated by multiplying the value of the actual runoff for the period October to February, inclusive, expressed in per cent of "normal," by the value of the weighted mean water-content of the snow-pack on March 1, expressed in per cent of "normal," by 1.2, and expressing this final result as a decimal (see Fig. 6 for curve showing values of X).

Determination of factor Y in general equation

(15) The amount of runoff which will obtain from the precipitation which occurs during the runoff-period will also depend upon conditions of soil and ground-water prior to the runoff-period. The ratio of runoff to precipitation can be determined fairly accurately from past experience, and thus Y for any given amount of precipitation can be evaluated. However, since the actual precipitation which will occur cannot be determined in advance, Y must be selected for assumed values of precipitation. A curve showing the proper values of Y to be used in the equation may be constructed by plotting observed values

of runoff against observed values of precipitation, with a proper deduction being made for the runoff which was the result of the melting of the snow-pack which existed at the beginning of the period (see Fig. 7 for curve showing values of Y).

Prediction of March to July, inclusive, runoff for 1940, based on revised procedure

(16) Figure 8 shows the predicted runoff for the period March to July, 1940, inclusive, as determined from the general equation of runoff described in paragraphs (11) and (12). The upper and lower limits of the curve of predicted runoff correspond to the maximum and minimum amounts of precipitation for the period March to July, inclusive, which have actually occurred during the past ten years. Based on the assumption that there is little likelihood of the actual precipitation being greater or less than these previously experienced values, the contingent forecast, then, does indicate the greatest amount and the least amount of runoff which will probably occur.

Accuracy of forecasts based on revised procedure

(17) It is obvious that the accuracy of the forecasts will depend upon the values of X and Y selected for use in the general equation. The curves shown in Figures 6 and 7 for determining these values were based upon conditions which occurred during the past several years, and they are therefore actually "rating curves" based on observed conditions.

(18) For conditions which will not differ greatly from those which have obtained during the past few years, it is believed that these curves should prove fairly reliable for forecasting purposes. As conditions change, it is planned to revise these curves from year to year to conform to the changed conditions, in much the same manner as the "rating curves" for river-discharge stations are revised when actual measurements show that the stage-discharge relation has changed.

Division Office, Missouri River Division,
U. S. Engineer Office,
Kansas City, Missouri

DISCUSSION

J. E. CHURCH (University of Nevada, Reno, Nevada)--Since the close of the season of snow-accumulation in the north is May 1 rather than April 1 (the date usually set for snow-surveying), the selection of the early date of March 1 deprives the snow-cover of some of its potency as a factor in runoff and correspondingly increases the apparent potency of the precipitation during March to July, assumed as the period of major runoff.

The periods of December to April and May to August would provide better groups of months for comparison. This might change the relative value 1/4 for the snow-factor K_S and 3/4 for the rain-factor K_P. Furthermore, the potency of the snow-cover is far greater than a similar amount of intermittent rain, for only one priming of the soil is required for the former and probably several for the latter, depending upon the number of rains and the interval between them. In the Susquehanna Basin where summer rain is badly depleted by interception, priming, and transpiration, the annual runoff is determined by the snow-cover rather than by the rainfall. Therefore, it was felt from a cursory view of this and adjoining watersheds in the East that minor snow-cover provided major annual runoff. However, this belief must be tested by actual computation, for according to Charles F. Brooks of Blue Hill Observatory only 10 to 20 per cent of the annual precipitation in this region falls in the form of snow.

It is doubtful also whether the winter runoff can provide a reliable index of soil-moisture or runoff-trends, for temperature is the prevailing factor in runoff during the winter, although in the lower areas of the streams, high winter runoff will prime the stream-channel and reduce waste.

Nevertheless, Mr. Freeman's plan of preliminary snow-surveys March 1 will be very valuable for determining the runoff in terms of the disappearance of the snow. A series of surveys March 1, April 1, and May 1, will aid particularly in revising the forecast. Such has been Mr. Elges' experience with snow-surveys March 1 and April 1 in the Humboldt River Basin, Nevada, where March 1 has been considered the end of the season of accumulation.

The effect of rainfall can best be determined from the study of the graph of runoff during storm-periods. Such rains are most effective on snow or on meadow and irrigated ground. Sage-brush lands provide little runoff from rain. The gain is dependent upon the heaviness or continuity of the rain. For example, during the light but almost continuous rain of May 1-11, 15-22, and 29-31, 1930, which furnished a total precipitation of 3.07 inches average for six stations, or 249.2 per cent of normal for the month, an additional runoff of approximately 37,000 acre-feet occurred at the gaging-station at Palisade, or approximately 14.5 per cent of the seasonal normal for March to July.

Small quantities of precipitation, even if bunched, have little noticeable effect. The precipitation of 0.29 inch, June 19-20, 1930, made no noticeable rise or even pause in the fall of the river at Palisade. Likewise the precipitation of 0.19 inch July 9-10 caused a gain in the runoff of only 270 acre-feet on July 11-15.

These latter results are to be expected, for the precipitation of June to July falls mainly upon dry soil, and unless unusually heavy has only a minor effect upon stream-flow. For example, 2.49 inches of precipitation on June 10-17, 1929, caused a net runoff of 14,000 acre-feet, or five per cent of the total seasonal runoff. Again in 1913, the June precipitation of 2.66 inches, or 340.7 per cent of its normal, apparently created a gain of only 40 per cent in the expected runoff for the month or 27,500 acre-feet, and the July precipitation of 1.23 inches or 233.0 per cent of its normal created a gain of only 50 per cent for the month or 13,000 acre-feet. In terms of total seasonal runoff, this means a gain of only ten per cent for June and five per cent for July. Even if the total flow in the river were credited to the precipitation, the gain would still be only double the above percentages or a total of 30 per cent. Such occurrences, though desirable, are naturally unusual.

Unfortunately, the summer precipitation on the eastern side of the Continental Divide is of the thunder-storm type and is therefore intermittent and weak, and furthermore is local rather than widespread.

O. W. MONSON (Montana Experiment Station, Bozeman, Montana)--Does the term "weighting" cover the proportion of runoff resulting from snow-melt as compared with the proportion resulting from rainfall?

A date later than March 1 would prove more reliable for snow-surveys since it would cover a larger period of accumulation. This of course requires location of snow-covers at higher elevations. Months of March and April are usually months of heavy precipitation and therefore could easily change values of K_S and K_P.

THE SNOW-MELT PROBLEM AS AFFECTING THE DESIGN OF FLOOD CONTROL-WORKS

Otto N. Rugen

The various effects of melting snow have attracted the attention of engineers and scientists for quite some time. A number of men have made investigations of the phenomena and each has brought to the subject a viewpoint and approach colored by his past experience and the requirements of the branch of endeavor in which he was engaged. Thus the meteorologist was primarily interested in the effects that bodies of snow might have on the temperature, humidity, and movements of the atmosphere. The geologist was interested in the formation and physiographical effects of glaciers. The hydroelectric, water-supply, and irrigation engineers were interested in the amount of water that would be available for beneficial use in any particular season, or the minimum amount that could be relied upon, in order to properly plan the season's operations and thus get the most beneficial use from such water as would be available.

The flood-control and river engineer has an entirely different problem. From the standpoint of design of structures for flood-protection or navigation, he wants to know at any point what the maximum rate of flow can be. In this he is not so much interested in the amount of water that would be yielded by a snow-field in any particular season as in the maximum amount that would be yielded from that area under the most adverse conditions and especially the rate at which the yield would come.

As illustration, reference might be made to the Santa Ana River flood in the spring of 1862. According to the testimony of old inhabitants, there had been a snow-cover of several feet in the upper elevations of the San Bernardino Mountains. That spring a storm of several days' duration occurred with probably a little higher than normal precipitation, during which time the snow-mantle absorbed a considerable part of this precipitation and held it in storage. The last day of the storm the wind shifted to the south and was quite warm. As a result, a large part of the snow-mantle melted in one day, releasing not only its own water-equivalent but also the precipitation stored up during the first part of the storm, and as a consequence the Santa Ana Valley experienced the highest flood of which we have a historical record. It might be mentioned that if this shift in the wind had not occurred and the snow-fields had followed a normal melting season of two to three weeks' duration, the area would probably have experienced only an average high flood.

Where regulation is introduced into the stream-flow, either artificially through the construction of regulating reservoirs or naturally through lakes and the channel-storage of the stream itself, the total volume under the runoff-hydrograph is of equal importance as the peak-rate of flow. While a knowledge of this volume in any particular season, as derived by snow-survey methods, would be advantageous, particularly for the regulation and guidance of river-traffic, it is not as important for the designing engineer as a knowledge of the maximum volume that can occur at the location in question. To answer this question it would be necessary to have long-time records of moisture-content in the snow-fields and extend these by the probability-method. In most instances where a design is contemplated, the records of these basic data are not available. Unless the meteorologist can, by the methods of air-mass analysis, develop the worst meteorological conditions for the area, the designing engineer is up against a blank wall.

To make intelligent hydraulic designs of structures controlling stream-flows, the underlying hydrology must be fully understood in all of its branches and ramifications. To do this, it is necessary to develop reliable basic data of all related factors and also methods of analysis by which these data can be properly interpreted and a design-procedure established. The correct interpretation of past occurrences of these phenomena is often rendered more difficult by the fact that data may have been incompletely reported due to breaks in the observations. There often is a simultaneous occurrence of different phenomena, the effects of which mask each other, and often what is presented as observed data is simply someone's interpretation of observed facts to fill in gaps in the record or to attempt to separate the effects of these conflicting phenomena. Without such an understanding of each of the agencies that contribute to the final result, a design would be based on a guess and not a correct engineering analysis.

As an illustration, the storm of March, 1938, would have furnished information that would have been valuable in developing the design of a flood-control basin and other protection-works at the mouth of San Antonio Canyon in Los Angeles County if the computed hydrograph of this stream had been based on continuous observations. As it was, satisfactory data were available to establish the rising stage and possibly the peak-flow of this hydrograph, but direct observational data of the falling stage were lacking. A correct interpretation of this falling stage is of great importance, not only for the establishment of the total volume under the graph but also for a check against the basic data and methods of analysis used in the area for computation of runoff. A considerable portion of this drainage-area was covered with snow at the time of the storm and the effects of the snow-field and the rainfall masked each other so that it became necessary to investigate the possible effects that this snow-cover might have had on the runoff.

From the foregoing it can be seen that the problems facing the flood-control engineer in connection with the effects of snow are of a different nature than those of other investigators. They possibly require a more exacting study in which the knowledge and methods of the meteorologist, physicist, and astronomer, as well as the hydrologist, will have to be called on to understand not only what has taken place in specific instances but also what can possibly take place at those locations.

In order to develop the points at which research and further study will have to be made so that the flood-control engineer can have a workable scientific method of analysis and design procedure, it may be advisable to trace through a melting season in a snow-field.

The writer is not as familiar as he should be with all the facts concerning the formation of a snow-field but believes that the precipitation of atmospheric moisture in the form of snow possibly follows along the same lines as that in the form of rain. If so, there will be in any region variations of precipitation with altitude that can be plotted in the form of isohyets, but due to drifting these will probably take a slightly different shape. A cross-section of the snow would then be roughly in the shape of a wedge with the greatest thickness at the top and feathering out at the lowest elevation at which the snow can be formed. The laws governing the size and shape of this wedge of snow with its accompanying isohyets for any drainage-area may then be considered as the first point to which the attention of the meteorologists might be called either for research or codification of the existing knowledge.

Due to physical characteristics of the snow itself, it gradually changes its form and acquires a granular structure accompanied by shrinkage in volume and increasing density. Diurnal variations in solar radiation and air-temperature at this time may cause melting at the surface which immediately becomes refrozen, forming a thin sheet of glare-ice over the snow. After a fresh snowfall this process would be repeated, so that at the beginning of a melting season the snow-cover may consist, not of a mass of flaky snow-crystals, but of a granular mass of ice-crystals, interspersed with thin sheets of solid ice, having a temperature below 32°F, a density considerably above that of freshly fallen snow and most likely a sheet-cover of glare-ice.

A curious situation can now occur. Rain, falling at this time, would produce practically 100 per cent runoff for a short length of time, depending on the thickness of this glare-ice cover. The heat in the rain would be given up to the ice at the rate of 144 degree-inches of rain per inch of melt, and the resulting melt-water would probably make up for the infiltration-losses through the ice. If this ice-cover is thick enough, it might be possible, under certain conditions, to produce a short high-intensity peak-runoff. The possible thickness that this ice-cover can attain might therefore be suggested as another problem for research.

After the melting of this glare-ice cover, rain would meet exactly opposite conditions. Due to the high infiltration-rate of coarsely granular snow, the rain would probably all be absorbed with no sheet-flow over the surface. At the beginning of the season, the low snow-temperature would cause it to freeze in thin sheets over the existing crystals. Mechanical effects of impact and the added weight would cause some settlement and as a result there would be an increase in snow-density and temperature without any runoff or water reaching the surface of the underlying soil.

After enough heat has been added to the snow to raise its temperature to 32°F, any supply of moisture, whether from rain or from the melting of the upper portion of the snow, would pass through it to the ground as through any other porous medium.

This water gets away from this surface by two processes: Infiltration into the soil and percolation through the bottom layer of the snow to its edge where it appears as surface-runoff. Robert E. Horton has made a very excellent study of these phenomena in his paper "Phenomena of the contact zone between the ground surface and a layer of melting snow" [Internat. Ass. Hydrology, Bull. 23, pp. 545-561], to which attention is directed.

Mr. Horton brings out the point that a slush-layer will usually occur, consisting of particles of snow whose interstices are completely filled with free water moving by the force of gravity to some point of exit, and has developed a method of evaluating the depth of this slush-layer and the rate of outflow.

It can be immediately seen that the water held in this percolation-zone represents storage and this storage exerts a regulating effect on the resulting runoff. As George D. Clyde pointed out in his "Snow-melting characteristics" [Utah Agric. Exp. Sta., Bull. 231, pp. 20-21], the rate at which water leaves the snow is practically constant.

The writer has been engaged in extending this work to a study of the effects resulting from this storage. For a graphical representation of these effects reference is made to Plate 1, which was prepared to represent a typical condition of a rainstorm of three inches in 24 hours, one and one-half inches in one hour with a short high-intensity peak. As far as storage and outflow are concerned, the results would be the same whether the inflow were in the form of rainfall or snow-melt. From this graph it can be seen that the rate of outflow at the edge of the snow-bank is considerably less than the rate of inflow during the greater part of the period, although it is more at the latter end.

An examination of curve E leads to the development of some interesting hypotheses. This curve represents the amount of storage accumulated in a snow-bank having sufficient storage-capacity. The figures to the left of the graph indicate the thickness of snow, at a density of 50 per cent to provide the storage required by curve E. The point at which curve E crosses one of the horizontal lines, indicates the depth at which the snow at the outlet will be saturated and can hold no more storage.

What will happen at this point is largely a matter of conjecture. Under certain conditions of roughness and slope of surface, the entire mass may be moved mechanically in the same manner as the movement of water-lubricated "debris-flows." If this should happen, there might be a sudden rush of saturated slush into a stream that might cause a higher peak than that caused by rain falling on bare ground. Due to the bulking caused by the slush, it might produce stage-readings higher than the actual amount of water involved should indicate.

If there is no mechanical movement of the slush-body as a whole, any additional supply of water would move over it the same as over any other saturated medium. The "effective rain" would therefore suddenly jump from that indicated on "outflow-rate curve D" to that indicated by "inflow-rate curve A." In addition, the heat introduced by the supply-water may, by melting, weaken the cellular structure of the slush so that portions of it may become loosened and float off even if the mass as a whole does not move.

Beyond the point of saturation, the resulting runoff, therefore, will be absolutely unpredictable although it may possibly be stated in terms of limits.

Unfortunately, a study of this nature involves a great deal of tedious computation and does not readily lend itself to simple expressions. However, it is the hope of the writer that further investigation may develop correlations that can be simply expressed, possibly in terms of percentages or perhaps equivalent detention-time. These may be sufficiently accurate, within definite ranges, to be applicable to engineering design.

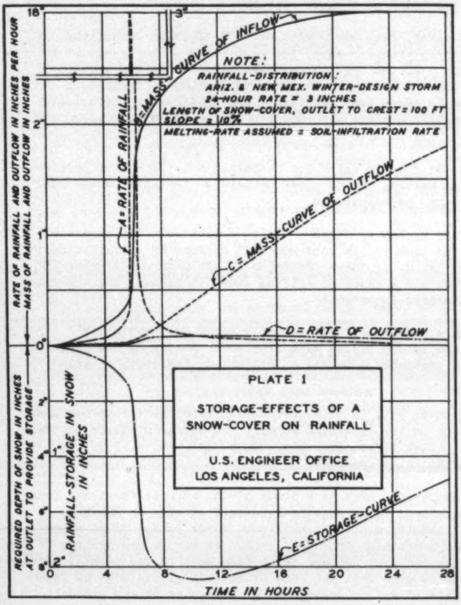


PLATE 1

STORAGE-EFFECTS OF A SNOW-COVER ON RAINFALL

U.S. ENGINEER OFFICE
LOS ANGELES, CALIFORNIA

Up to this point we have considered only a unit-section through the snow-field. When it is recognized that the total water-supply to the snow consists of both rainfall and snow-melt, and that these are both variables, it can be seen that the situation becomes quite involved. In Plate 1 we have considered the effects of variation of rainfall with time. The effects of variation of rainfall with location will also have to be considered possibly by some method similar to that used in the "Rational method for rainfall-runoff."

Variations in the rate of snow-melting both with time and location also affect this problem. Along with the heat introduced by the rain-water, there is always heat introduced from other sources that would cause melting which, simply for purposes of identification, we may call "normal melting." These various sources of heat-energy that affect the problem may be considered as follows: Radiation-energy from the Sun, from the Earth's atmosphere, and from the snow itself; heat transferred by conduction and convection from the atmosphere; and heat transferred by conduction from the ground below the snow.

The effects of these all involve a transformation of energy from one form to another.

In any consideration of atmospheric phenomena involving transformation of energy, it must be appreciated that the only original source of energy is radiation from the Sun. It is also recognized that over a period of time there is no increase or decrease in the total energy on the Earth and that therefore an energy-equilibrium has been established whereby the Earth as a whole radiates back to space as much energy as it receives. The intensity, however, of both solar and earth-radiation varies with location. As a result there is an excess of solar radiation at the equator and an excess of earth-radiation at the poles. The attempt of the atmosphere to equalize these excesses is the primary cause of most meteorological phenomena. In doing this, air-masses are transported from the equator to the poles and back again accompanied by various manifestations of energy--motion, heat, electric charge, vapor-pressure, and change of state of some of its elements.

The only true balance that can be established at any point is one that takes into consideration all of these manifestations of energy in its various forms. These are so varied and the relationship between them so complex and unpredictable that it is obviously impossible to do this. Any particular area of the Earth cannot therefore be isolated and a true balance set up between incoming and outgoing energy, nor can it be considered as a self-inclosed system independent of the rest of the Earth's atmosphere.

Several such attempts have been made but they either ignore some items of energy or they hold true only for specific cases where certain of the variables have been eliminated. It is probable that a completely scientific approach to a problem of this sort is impossible and the best that can be hoped for is a solution, based on a combination of analysis and correlation, that is believed to have a reasonable probability when certain basic assumptions are made.

While it is true that the Earth as a whole is in a position of equilibrium and stability with respect to energy-content, the atmosphere is not, and is either parting with or gaining in energy-content or changing its form.

The energy in the atmosphere is both potential and kinetic; the potential energy is represented by sensible heat, atmospheric and vapor-pressure, static charges, the atomic energy of the component elements, etc.; the kinetic energy is represented by air-movements such as the movement of an entire air-mass and the turbulence within it, and these are all variable quantities.

When an air-mass passes over a surface having a difference in temperature at its contact, it undergoes changes in both its potential and kinetic energy. If the air is warmer than the surface, it will lose heat-energy to the surface, gain vapor-pressure under certain conditions, and gain stability which is the same as losing turbulence. The gain in vapor-pressure will also be accompanied by an increase in both the atmospheric absorption and emission of radiation-energy. If the air is colder than the surface, the opposite effects can be observed.

Variations in the moisture-content and vapor-pressure of the air can be studied by means of application of the Dalton hypothesis. Considerable work has been done in this connection, but most of it has been for the purpose of determining evaporation from open-water surfaces. The direct sublimation from snow and ice has not as yet received the attention it should have. Variations in the amount of heat-transfer and changes in the kinetic energy, however, become a complex thermodynamic problem. If the assumption is made that the velocity of travel of the air-mass is constant over the area under consideration, it is believed that variations in the amount of heat-transfer can be computed by means of the Colburn formula which considers this as a problem of heat-transfer under conditions of turbulent flow and known temperature-differences.

The assumption is probably warranted in dealing with snow-fields of the size likely to be encountered in these investigations but could not be used in fields of continental dimensions.

The amount of heat transferred between a fluid and a surface depends on the thermal properties of the skin-film of the fluid at the contact and can be expressed as follows

$$Q = ZAhk$$

where Q = total heat transferred in BTU over an area A square feet in time Z hours, h = difference in temperature between the fluid and surface in °F, k = thermal conductivity of skin-film = BTU per square foot per hour for degree-F difference in temperature. The unit-heat transfer per hour would then be $(Q/ZA) = hk$. The Colburn formula [see Croft "Thermodynamics, fluid flow, and heat transmission," McGraw-Hill 1938, p. 217, and Trans. Amer. Inst. Chem. Eng., pp. 29-174, 1933] gives a means of evaluating k as follows:

$$(k/C_pG)(Pr)^{2/3} = 0.0007 + 0.065\,(Re)^{-0.32}$$

where G = weight velocity = weight of fluid per unit cross-section area per sec in lb/ft^2/sec; C_p = heat-capacity in BTU/°F/lb wt of fluid; (Pr) = Prantl number = $(\mu C_{xp}/k')$, where μ = viscosity of medium in lb/sec/ft^2, C_{xp} = specific heat at constant pressure in BTU/lb/°F, k' = conductivity of medium in BTU/sec/ft^2, and (Re) = Reynolds number of medium. According to Brunt, the Reynolds number for the atmosphere is of the order 10^9.

Applying appropriate values to this expression, values of k were computed for different values of h at a velocity of ten miles per hour. Plotting these values then as hk against h it was found by curve-fitting methods that these followed the expression $hk = (1.2h + 0.015h^2)$

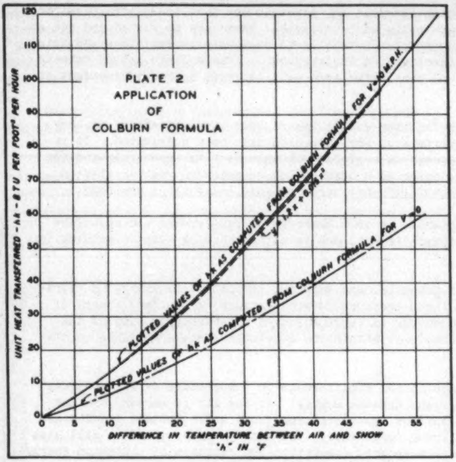


PLATE 2
APPLICATION
OF
COLBURN FORMULA

(see Plate 2). The unit heat-transfer is essentially some function of the temperature-difference and wind-velocity, and the general expression can be set as follows

$$hk = C \cdot f(h) \cdot f(V)$$

According to the above derivation from Colburn's formula, $f(h)$ is proportional to $(1.2h + 0.015h^2)$ and $f(V)$ to $C'V^n$, where n is some positive power.

The general expression for unit heat-transfer then becomes $hk = C(1.2h + 0.015h^2)(V^n)$.

This expression was checked against Clyde's experiments at Gooseberry Creek, Utah, and the Wagonwheel Gap experiments. After allowances for solar radiation, evaporation, etc., had been made, it was found that, with values of $C = 0.4$ and $n = 0.5$, a very close correlation was obtained when h is taken in terms of mean daily temperature.

Using these values the above formula for unit heat-transfer from a turbulent air-mass becomes

$$hk = (0.48h + 0.006h^2)\ (V^{0.5})$$

This formula has also been checked against observed temperature-drops in air-masses moving over snow-surfaces and a reasonable degree of correlation was obtained.

It is to be noted that while the general form of the expression was derived analytically, the numerical value of the constants are empirical and are based on a rather limited number of

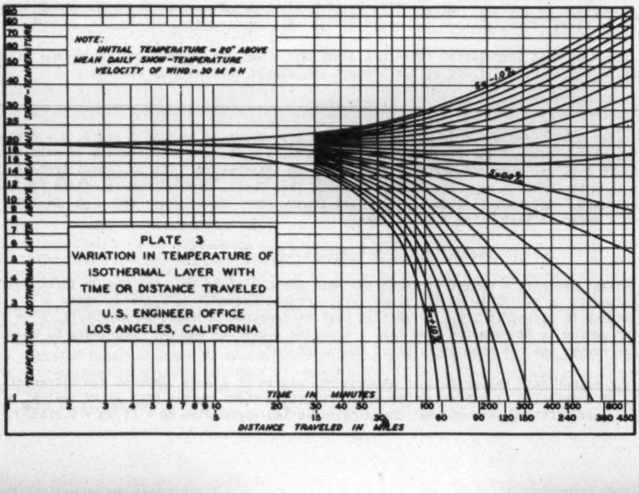


PLATE 3
VARIATION IN TEMPERATURE OF
ISOTHERMAL LAYER WITH
TIME OR DISTANCE TRAVELED
U.S. ENGINEER OFFICE
LOS ANGELES, CALIFORNIA

NOTE:
INITIAL TEMPERATURE = 20° ABOVE MEAN DAILY SNOW-TEMPERATURE
VELOCITY OF WIND = 30 M P H

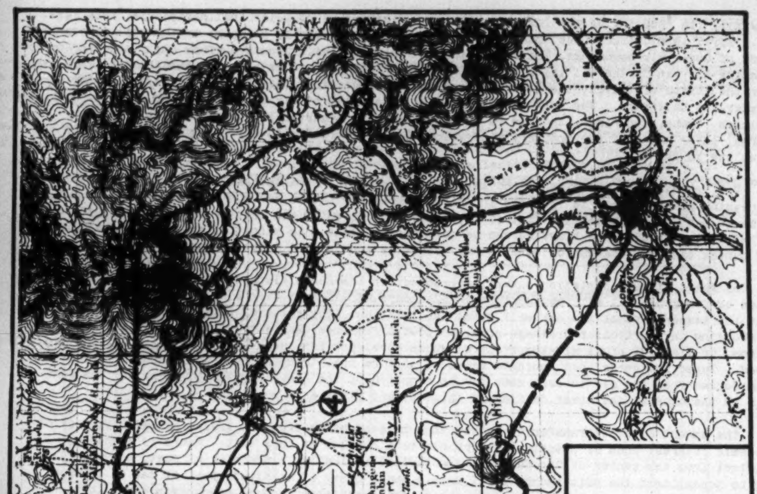


PLATE 4
PLAT SHOWING ISOTHERMS
AND ZONES OF EQUAL MELTING
RIVER DE FLAG DRAINAGE AREA
LITTLE COLORADO BASIN

observations while other factors that affect the problem are assumed constant, such as the composition of the air, amount of solar radiation, etc. It is the writer's belief that a true expression for the transfer of heat from the atmosphere is of vital importance to this problem, and it is hoped that further research along this line will be carried on to improve it. Such research would probably show that both C and n in the above general expression are not constant but are themselves variable with values depending on some of the other considerations. Both C and n will also have different values if the diurnal variation of air-temperature is considered and an expression for the instantaneous transfer of heat is derived.

This formula is of value not only for determining the amount of heat transferred to the snow but also for determining temperature-changes in the air as it passes over the snow.

H. Wexler [in "Cooling of the lower atmosphere and structure of polar continental air," Mon. Wea. Rev., April 1936], traced the transformation of polar maritime air to polar continental air by means of upper-air soundings. He showed that in passing over a ground-surface that is colder than the air, an isothermal layer is developed at the bottom of the air-mass and that the farther the length of travel, the lower will be the temperature of this isothermal layer and the greater its thickness. The writer has made similar studies of air-soundings taken at Cheyenne, Billings, Omaha, and Fargo, and has in several instances observed the development of this isothermal layer and that for ordinary wind-velocities it increases in thickness at the rate of about one km per day.

The increase in the thickness of this layer probably indicates that, due to turbulence, an increasing amount of air is involved in the heat-transfer. This has not been definitely proven to be so but on the assumption that it is, depletion-curves of the heat or temperature in the air with time or distance traveled can be developed. Plate 3 is submitted as an example. Similar curves can be prepared for other wind-velocities and initial temperatures.

By means of such depletion-curves, corrected for the normal lapse-rate if the travel is upgrade or downgrade, it will be possible to transpose an air-mass over a snow-field and determine what the temperature of the air will be at any location. The value of this lies in the fact that in studying any particular drainage-area, various air-masses can be transposed to it and isotherms, or lines of equal air-temperature can be developed for the meteorological conditions assumed. These isotherms then indicate zones of uniform heat-transfer, and the amount of heat transferred from the air in each zone can be computed by the above formula. The writer has done this in the case of the River de Flag in Arizona, and Plate 4 is submitted as an example.

The amount of heat transferred to the snow by conduction from the ground below it is more of academic interest than of practical importance to a problem of this sort. There is a thermal gradient from the center of the Earth to the surface indicating a transfer of heat, but according to Schoklitsch the unit-amount is of such a small order of magnitude that it can be ignored. At the edge of a snow-field the soil can absorb solar radiation and by conduction carry it to the bottom of the snow, but this would be of importance to only a very limited part of the entire field.

Also snow itself is not totally absorbent to solar radiation but will transmit certain wave-length bands of the solar spectrum to the ground beneath it if the thickness of the snow is not too great. The radiation absorbed by the ground is transformed into sensible heat which can be transferred to the undersurface of the snow by conduction. The amount of heat involved is very difficult to compute because the coefficient of radiation-absorption for snow has not as yet been satisfactorily determined. However, this also is of minor importance to the problem.

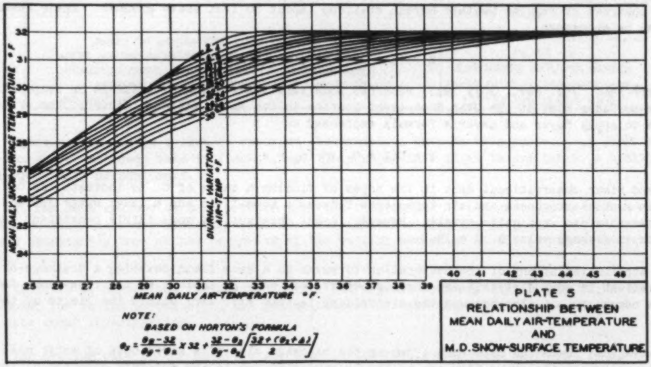
Radiation-exchanges--The computation of the net amount of radiation-energy absorbed by snow is a complicated problem in physical astronomy. No attempt will be made to present a solution for this problem except to point out its essential elements. A search of the literature will reveal several excellent studies of its component parts but as yet no one has combined them all into a single presentation. The writer has been engaged in such an attempt but as yet is not satisfied with the results.

The amount of radiation-energy emitted by the Sun has been the subject of considerable study, and Richardson, in "Insolation and evaporation" [Trans. Amer. Soc. Civ. Eng., v. 95, 1931], gives a table of I_{ex}, that is, the amount of insolation or solar energy at the exterior of the atmosphere, for different latitudes and different times of the year. Of this, a certain amount will be reflected back to space by the atmosphere and a certain amount absorbed by it, so that only some proportionate part reaches the surface of the Earth. According to Beers' law for radiation-absorption, the amount of radiation-energy transmitted through a medium would depend on the coefficient of absorption and varies with the thickness of the medium through which it passes on an inverse logarithmic basis. The altitude of the location therefore has a very important bearing on the amount of insolation reaching the surface of the snow.

The coefficient of absorption for the atmosphere also is not constant. According to Wexler (in the reference cited above) both water-vapor and CO_2 gas are good long-wave absorbers and the solar spectrum shows strong absorption-bands at several different wave-lengths. The cloudiness of the atmosphere also has a very material effect on the amount of radiation reaching the Earth's surface. These items affecting it are all so variable that it is probable that the proper coefficient of absorption for the various conditions to be encountered at any location can only be determined experimentally by means of direct insolation-observations.

As most snow-studies will be made in northern latitudes and at times of the year when the zenith-angle of the Sun is quite large, the attitude of the ground-surface, especially whether it slopes toward the south or toward the north, will have an important bearing on the unit-intensity of the insolation at the snow-surface. Bates and Henry in the Wagonwheel Gap experiments [Mon. Wea. Rev., Sup. 17, 1922, and Sup. 30, 1928] present a method for making this correction.

Of the total amount of insolation reaching the snow-surface, only a proportionate part will be absorbed by it, some being reflected from the surface and some being transmitted through it to the ground below the snow. Brunt gives the radiation reflection-factor of snow as 0.75. As mentioned above, the amount of radiation transmitted through the snow cannot be directly computed until a satisfactory determination of the coefficient of absorption for snow is made, but it is the writer's belief that for the thickness of snow encountered in most problems, this will be negligible.



NOTE:
BASED ON HORTON'S FORMULA

$$\theta_s = \frac{\theta_g - 32}{\theta_g - \theta_a} \times 32 + \frac{32 - \theta_a}{\theta_g - \theta_a}\left[\frac{32 + (\theta_a + \Delta)}{2}\right]$$

PLATE 5
RELATIONSHIP BETWEEN
MEAN DAILY AIR-TEMPERATURE
AND
M.D. SNOW-SURFACE TEMPERATURE

In addition to the solar radiation absorbed by the snow, the "black-body" radiation of the snow itself and of the atmosphere will have to be considered. These can each be determined by the Stephan-Bolzman formula and reference is made to Brunt for the procedure. In doing this, consideration must be given to the surface-temperature of the snow. Both Wexler [Mon. Wea. Rev. April 1936] and Horton and Leach [Mon. Wea. Rev., April 1934] made studies of the snow-surface air-temperature relationship. Due to the excess of back-radiation at night, the night temperature of the snow-surface will drop to considerably below 32°, and the mean daily temperature may, depending on the diurnal variation and mean daily air-temperature. Using the method proposed by Horton and Leach, the writer has constructed the graph shown in Plate 5, which indicates the mean daily snow-surface temperature corresponding to a given mean daily air-temperature for various diurnal variations in air-temperature.

The algebraic sum of the heat-accretions from the various sources outlined above is used up by the snow in three ways: (1) Evaporation, that is, direct sublimation from the snow and evaporation from any melt-water present; (2) raising the temperature of the snow to 32°F; and (3) melting of the snow after it has reached that temperature.

A study of evaporation is of considerable importance to this investigation because most of the studies on snow-melting that have been reported were made under conditions where appreciable evaporation-losses were encountered. To properly evaluate the various factors in the problem, these losses had to be considered. In some areas it might be possible, for design-purposes, to assume meteorological conditions that would produce negligible evaporation-losses, whereas in other areas such an assumption would not be proper.

The classical conception of the Dalton hypothesis makes evaporation some function of the humidity-deficit of the air and the ground wind-velocity. In its general form this can be expressed

$$E = A(1 + CW^n)(e_w - e_d)^m$$

where e_w = saturated vapor-pressure at temperature of snow-surface, e_d = atmospheric vapor-pressure, A and C are factors expressing possibly the roughness of the surface and turbulence of the air, and n and m are exponential. It would seem to be a simple matter to determine empirically, from existing observational data, the proper numerical values for these factors. Due to the fact that wind-velocities are not measured at the ground-surface but some distance above it and because of the scarcity of meteorological stations, long-range interpolations have to be made in both humidity-deficit and wind-velocity; the various attempts to derive these have not given consistent results.

Meyers and Levan in Engineering News-Record, April 1, 1937, in studying evaporation over bodies of water, expressed E in terms of inches evaporated per month, neglected n and m, and found A to be 1 and C to be 0.1 when the atmospheric vapor-pressure and wind-velocity were measured as observed at regular Weather Bureau stations (about 50 feet above ground). Their results would then be expressed

$$E = (1 + 0.1w)(e_w - e_d)$$

F. S. Baker [Mon. Wea. Rev., July 1917] recorded some very interesting experiments on evaporation from snow-surfaces made at the Utah Experiment Station in the Manti National Forest. The writer attempted to apply Meyer and Levan's formula expressed as

$$E = C(1 + 0.1w)(e_w - e_d)$$

to this and other observational data in the hopes of finding a value of C, to indicate the difference in surface-roughness and air-turbulence between a snow-field and a level water-surface. The results obtained were quite erratic; however, eight observations gave fairly consistent results with an average value of C = 13.7.

The application of any of the evaporation-formulas to a snow-field covering a drainage-area of large extent is very difficult and unsatisfactory, not only on account of the long-range interpolations necessary but also because the controlling factors will vary within the limits of the field.

Floating-pan tests indicate that a pan on the windward side of a large body of water will have a higher evaporation-rate than one on the leeward side due to the moisture absorbed by the air and consequent raising of its relative humidity.

Due to the progressive cooling of the air as it passes over a snow-field, its relative humidity will also increase from this cause. It is the writer's belief that these two effects can be expressed in a curve showing the change in rate of evaporation with distance traveled by the air. With such a curve it should be possible to transpose any given air-mass to a snow-field and establish lines or contours of equal evaporation over the field. In drainage-areas of small extent this is not essential but in large ones it would probably be of importance.

Heat consumed in raising temperature of snow--As mentioned previously, at the close of the winter season, the snow-cover will most likely have a temperature below 32°, and the first effect of melting is the congealing of the melt-water around the ice-crystals as it percolates downward. Before runoff can appear, therefore, the temperature of the entire thickness of the snow has to be raised to 32°F. At first glance it would appear that for design-conditions, the snow-field can be assumed to have reached this stage and that a knowledge of the temperature-characteristics is unessential. This would be true if the entire snow-field were level and melting were taking place uniformly, which, however, is a very exceptional case. In most drainage-areas there is a large range in elevation so that the lower portion may be finishing its melting season before the upper portion has started. Consequently, all the processes involved in a melting season are taking place simultaneously in different parts of the field. As the problem requires the runoff contributed by the entire snow-field, it can readily be seen that a knowledge of these temperature-characteristics and their variations both with location and time is quite important.

Sverdrup, Wexler, and Horton and Leach have all studied the temperature of the surface of the snow under various conditions. These findings, however, apply to only a relatively shallow depth. Due to its low coefficient of thermal conductivity, there can be wide fluctuations in the temperature of the surface without materially affecting the temperature of the rest of the snow.

WIND-VEL	ZONE		INCHES WATER MELTED		
			FEB	MAR	APRIL
50 M P H	1	PER DAY	0.00	0.00	0.00
		PER DAY PER °F	0.00	0.00	0.00
"	2	PER DAY	0.00	0.00	0.02
		PER DAY PER °F	0.00	0.00	0.002
"	3	PER DAY	0.96	1.11	1.22
		PER DAY PER °F	0.077	0.088	0.097
"	4	PER DAY	1.95	2.16	2.27
		PER DAY PER °F	0.118	0.131	0.138
40 M P H	1	PER DAY	0.00	0.00	0.00
		PER DAY PER °F	0.00	0.00	0.00
"	2	PER DAY	0.00	0.00	0.00
		PER DAY PER °F	0.00	0.00	0.00
"	3	PER DAY	0.78	0.92	1.03
		PER DAY PER °F	0.062	0.074	0.083
"	4	PER DAY	1.69	1.83	1.94
		PER DAY PER °F	0.102	0.111	0.117

BASED ON ASSUMPTION OF A TROPICAL PACIFIC AIR-MASS, HAVING PROPERTIES INDICATED BY SAN DIEGO SOUNDINGS, BEING TRANSPORTED TO DRAINAGE-AREA ASSUMED WIND-VELOCITIES: FIRST DAY AT 50 M P H, BALANCE AT 40 M P H

PLATE 6
ESTIMATED MELTING-RATES
RIVER DE FLAG DRAINAGE-AREA
LITTLE COLORADO BASIN

There appears to be a lack of recorded observational data on this subject--at least the writer has as yet not been able to find it, and it is hoped that if it is available, a bibliography listing it will be published.

It has been assumed by some writers that the temperature of the ground below the snow is at 32°F, and that the temperature-gradient is a straight line from the ground to the surface. This is not necessarily true at the beginning of the melting season or at all points within the snow-field.

It is to be hoped that the meteorologists can suggest some way that proper values can be assigned, for design-purposes, to the ground-temperature and thermal gradient within the snow at any site under investigation.

The melting rate at any location and time is the resultant of the different processes listed above. It is dependent not only on the temperature of the air but also on the latitude and elevation of the location, the time of the year, the cloudiness of the atmosphere, the humidity-deficit in the air, and the wind-velocity. These are all variable and there can be no such thing as a "melting constant," and the numerical value for the depth of melt-water produced per unit of time by a unit temperature-difference as obtained from observations made at one location and under certain conditions cannot be used at another location and uhder other conditions.

As an illustration, computed melting-rates for the zones shown on Plate 2 and for certain assumed meteorological conditions are presented in Plate 6 to indicate the wide variations that can occur within a single drainage-area.

Rain falling on this area would encounter very different conditions in different parts of the area. One part could be at the beginning of its melting season with a thick snow-blanket, capable of absorbing the rain or possibly having a glare-ice cover, whereas another part would be at the end of its season and produce a high runoff due to the saturated condition of the soil and perhaps mechanical transport of slush-ice.

In summarizing these effects, it may be said that the characteristics of the runoff resulting from rain falling on a snow-field are almost independent of the characteristics of the rainfall. They depend more on those of the snow-cover and the soil underneath it and these are variable both with the time of the year and location. The resulting runoff can vary from 0 to over 100 per cent of the rainfall, depending on the time and location, and it is possible within a single drainage-area to have one effect in one part of the area and the opposite effect in another.

If the hydrologist responsible for a flood-control structure had a back-log of stream-hydrographs extending over a long enough period of time, his job would be relatively simple. In most cases he is called upon to give an answer where this back-log is of too short a duration to properly establish frequency-curves. Even such records as he has available may be misleading, as it often happens at the times of the great floods that the recording stations are washed out and the record in which he is most vitally interested is missing. It can be seen from the above discussion how difficult it is to fill in this gap in the record and to say exactly what did happen in any storm even with a thorough knowledge of local conditions and all the contributing factors. Possibly the best that can be hoped for is an estimate based on the elimination of those combinations of factors that mature judgment would indicate to be improbable. In doing this, there are bound to be differences of opinion.

It is the writer's hope that, with a more thorough understanding of the principles involved, it will be possible to transpose various air-masses to the area under consideration and develop synthetic melting-seasons. These should indicate what hydrographs are possible from a given area, and perhaps by a mathematical analysis, their probable frequency of occurrence. If this can be done, it should be possible to establish points by which frequency-curves based on existing records can be more safely extrapolated.

Acknowledgments--The writer wishes to gratefully acknowledge the valuable assistance afforded him in these studies by Herbert Shapiro, Junior Engineer, especially in connection with the development of the application of the Colburn formula and by Frederick Cline, Associate Engineer, Richard Altman, Engineer, Ben. C. Williams, Engineer, and James G. Jobes, Senior Engineer, for assistance in bibliography, preparation of plates, and valuable criticism.

Associate Engineer, U. S. Engineer Office,
Los Angeles, California

DISCUSSION

J. E. CHURCH (University of Nevada, Reno, Nevada)--Mr. Rugen's conclusion "that the characteristics of the runoff resulting from rain falling on a snow-field are almost independent of the characteristics of the rainfall" is basic in the study of floods. The snow may absorb, transmit, or join the rain as additional runoff, depending upon its depth, temperature, and density.

However, ice-strata on or in snow are probably never sufficiently continuous to transport rain to the streams. The ice would either be melted by the warmer rain or the rain would more probably be cooled to ice. If the rain is copious, outlets through the crust would probably be found to the snow beneath.

The snow-cover rarely melts until the mass has become homogeneous and saturated by the percolation of melt-water. The density of snow or ripeness at which saturation occurs depends upon the original density of the snow. At lower elevations, where the snow-crystals are fluffier, ripeness may occur at density of 35 to 40 per cent. At high elevations where the snow is windswept and finer in grain, ripeness will probably occur only at density of 45 to 50 per cent.

Slush usually represents the final stage in melting and therefore should occur only in minor quantity. In this respect it differs from ice (either drift or frazil) which readily chokes the stream. A stream-bed would be clear of snow before any amount of slush would be formed. Only a dam-break could create a snow-jam.

Evaporation is a protector of basins against flood, though its power is small. In the case of chinooks, evaporation even tends to offset melting. At such times, the thin film of water created on ice is evaporated as quickly as it is formed. At altitude 9,000 feet on Mount Rose ice has been found to evaporate at the daily rate of 0.021 inch while slush evaporated at the rate of 0.120 inch or six times as fast. When moist, ice may be evaporated twice as fast as snow.

An experiment with black and white thermometers set in the snow indicates that the Sun can penetrate snow to the depth of 18 inches. If true, snow deeper than 18 inches is affected by the Sun only from above, but snow of shallower depth, since it permits earth-warming by the Sun, can be melted also from beneath. However, the amount of acceleration in melting has not been determined.

Suggestion has been made by Carroll F. Merriam of the Pennsylvania Water and Power Company that studies be made to see whether there is a critical temperature and density at which snow suddenly melts and thus aggravates floods. This problem could best be studied in the Susquehanna where winter melting normally occurs.

H. U. SVERDRUP (Scripps Institution of Oceanography, University of California, La Jolla, California)--Mr. Rugen states his problem clearly and discusses in detail all of the physical factors which affect the melting of snow-fields and the drainage from melting snow. I thoroughly agree with the concept that it is necessary to know the physical processes in order to arrive at satisfactory methods of estimating the runoff from snow-fields, and also I believe that special measurements should be made in order to determine empirical constants involved. One cannot expect to arrive at satisfactory results by making use of observations which have been made for other purposes and which therefore do not comprise all of the variables which are known to enter.

The energy for melting the snow or for evaporation is provided, as pointed out by Mr. Rugen, by processes of radiation and by heat-transfer from the atmosphere. It should be added that energy can also be supplied by condensation of water-vapor on the snow and, although Mr. Rugen's formula for evaporation shows that condensation will take place if the atmospheric vapor-pressure is greater than the saturated-vapor pressure at the temperature of snow-surface, he does not enter specifically upon the importance of condensation. A few remarks as to the different processes may be in place.

(1) Radiation--The total incoming radiation from the Sun and sky has been measured in so many localities that empirical formulas have been developed giving the total radiation-income on a horizontal surface as a function of the altitude of the Sun and cloudiness. Thus, direct measurements of the total radiation-income are not needed. Further studies of the reflection-loss appear desirable, however, although extensive studies have been made which show that the reflection-loss from newly fallen snow or from a glare-ice cover may be as high as 0.85, whereas the reflection-loss from a wet snow-surface is 0.65 to 0.60. The loss of heat by back-radiation can similarly be computed if the temperature of the snow-surface is known and if the air-temperature, the humidity of the air, and the cloudiness have been observed. Subtracting this loss of heat from the radiation-income after correction for reflection-loss, one obtains a fairly trustworthy figure for the amount of energy which is available for temperature-changes of the snow-cover, melting, and evaporation.

(2) Transfer of heat from the atmosphere--Studies, particularly by H. W. Ahlmann and associates, most of which have been published in Geografiska Annaler, have brought out that in the Scandinavian region the amount of energy transferred from the atmosphere contributes much more to the melting of the snow-cover than does the radiation. This conclusion is probably valid in general. The energy transferred from the atmosphere is partly given off as sensible heat and partly due to the transport of water-vapor from the atmosphere to the snow-cover and condensation of the vapor. The latter phenomenon has not received as much attention as it deserves, but a simple computation demonstrates that condensation must frequently take place. If, for instance, the air flowing over the snow-cover has a temperature of 40°F when the snow-surface has a temperature of 32°F, condensation will take place if the relative humidity of the air is greater than 75 per cent.

The semi-empirical formula for heat-transfer which Mr. Rugen has developed can probably be improved upon along the lines which he suggests, taking into account recent studies of the turbulence of the air. Mr. Rugen points out that coefficients which he introduces are probably not constants but will vary as conditions change and will particularly show diurnal variations. This is quite in agreement with the concept that the heat-transfer depends upon the stability of the stratification of the air which again depends upon the temperature-difference between the snow-cover and the air, and therefore varies during the day. Transfer of water-vapor can be dealt with in a similar manner.

(3) Evaporation--Evaporation from a snow-cover is probably of small importance. However, the melt-water which has percolated through the bottom layer of the snow to its edge, where it appears as runoff, may be subjected to intensive evaporation. This water often flows over ground which has been considerably heated by radiation. It will therefore be rapidly heated and when the vapor-tension increases correspondingly to the increasing temperature evaporation takes place. Thus, evaporation at the edges of the snow-cover may greatly reduce the total runoff, but this reduction is not due to evaporation from the snow itself.

(4) Rainfall--The direct effect of rainfall is, as stated by Mr. Rugen, probably of small importance. The temperature of falling rain deviates so little from the temperature of the snow that the rain does not contribute to any considerable melting, and the runoff resulting from rain must therefore depend mainly upon the characteristics of the snow-cover and the soil underneath it.

In conclusion, I wish to state that in my opinion it will be rational to conduct measurements of air-temperature, humidities, and wind-velocities over a snow-cover and, simultaneously, to measure the changes of the snow-cover both in respect to temperature and density of the snow. Measurements of radiation may not be needed if observations of cloudiness are made. If such measurements are conducted in detail during a period of time, which is long enough to comprise several characteristic meteorological situations, it should be possible to obtain a basis for rational empirical formulas by means of which possible runoff-curves can be computed corresponding to a given snow-cover and supposed meteorological conditions. This is exactly the procedure towards which Mr. Rugen's discussion leads.

DISCUSSION OF GEORGE W. MINDLING'S PAPER "DO CLIMATOLOGICAL AVERAGES SERVE ADEQUATELY AS NORMALS?"

Clarence Pedersen

This paper is a discussion of the question "Do climatological averages serve adequately as normals?", as presented by George W. Mindling of the Atlanta (Georgia) United States Weather Bureau before the American Meteorological Society in Milwaukee, Wisconsin, June, 1939. All tabulations used to supplement this discussion were abstracted from his original manuscript.

The present practice of the United States Weather Bureau is to show climatological normals as arithmetical averages. The question is, do these averages serve adequately as normals? To answer the question, one must state explicitly what interpretation is attached to the normal and then review the climatological records from all parts of the country for possible discrepancies.

A normal should represent the most common value of a series with a probability of being equalled or exceeded approximately 50 per cent of the time. This is the impression most people associate with the term "normal."

Since the arithmetical average does not always represent the most common value of a series, normals computed by this means are open for criticism. A fictitious example taken from Gavett's book on statistics is used to illustrate just how misleading the arithmetical average can be. In this example, ten trees of varying heights are shown in a man's dooryard; two trees are 40 feet high, five trees 50 feet high, one tree 60 feet high, and two trees 300 feet high. The arithmetical average of this group of trees is 99 feet, which is misleading in that none of the trees are near the computed average and 80 per cent of the trees are below average.

The hypothetical example given above has many parallels in our present climatological files. The snowfall-record at Waycross (Georgia) may be cited as one case. Through 40 years of record at this station the total snowfall was 6.4 inches, which gives an average of 0.2 inch, carried to the nearest tenth of an inch. This average leads one to expect a light snow-flurry each year, while in reality no snow was recorded during 32 of the 40 years.

The one characteristic of the arithmetical average that makes it undesirable for computing a normal is that the average is greatly influenced by extreme variants. This was apparent in the fictitious tree example. One should not lose sight of this whenever the arithmetical average is used for expressing the most representative value of a series. The average will consistently give a value which has better than 50 per cent of the occurrences below it. This remark is not confined just to our climatological data.

An examination of our snowfall-records reveals that the average greatly exaggerates the snowfall-expectancy of practically every locality in the country. This gross exaggeration may be shown by the snowfall-records taken from the Philadelphia (Pennsylvania) and Portland (Maine) climatological files.

The snowfall-records for Philadelphia reveal that 69 per cent of the months were below average for the 54-year record. Such an average is misleading to anyone other than an experienced meteorologist. This same discrepancy, but not so pronounced, is found at Portland, where snow occurs with more regularity than at Philadelphia. Here the number of months with less than average snowfall was twice those having more than average snowfall. The exact figures were 242 months with less than and 116 months with more than average snowfall. These statistics and others are to be found in our climatological files, leaving little doubt that the average is inadequate for showing snowfall-normals.

In general, the situation as regards precipitation is a little better, but records from all parts of the country indicate the same tendency, that is, the averages published by the United

States Weather Bureau are too high for normals. Practically no locality can live up to its reputation for rainfall as published in the climatological records.

Records of precipitation from 14 stations distributed over the country, with 60-year records, were examined. Table 1 shows the frequency of the monthly precipitation below and above the average. A résumé of the Table reveals that 5,896 months or 59 per cent of the months were below average. The average for the record at Seattle came the closest to representing the normal, with 54 per cent of the monthly occurrences below the average. San Francisco made the poorest showing with 64 per cent of its 720 months below average. The other 12 stations fell in between these percentages.

Table 1--Monthly precipitation-data in terms of the average

(60-year records)

Station	Number of months			Per cent of months		
	Below average	Above average	Aver-age	Below average	Above average	Aver-age
Portland (Maine)	404	316		56	44	
Cleveland	411	306	3	57	43	
Atlantic City	412	308		57	43	
Atlanta	411	305	4	57	42	1
Key West	442	277	1	61	39	
Duluth	399	318	3	56	44	
St. Louis	429	290	1	60	40	
Galveston	425	295		59	41	
Bismarck	427	291	2	60	40	
Denver	422	295	3	59	41	
El Paso	450	264	6	62	37	1
Salt Lake City	406	311	3	57	43	
Seattle	393	322	5	54	45	1
San Francisco	465	236	19	64	33	3
Totals	5,896	4,134	50	59	41	

Only four of the 14 stations, Atlantic City, Duluth, Galveston, and Seattle, revealed months where there were more occurrences above the average than below. Table 2 shows, for these stations, the number of times that precipitation was below average, above average, and just average for each of the 12 months during the 60 years examined. There were just five instances where the monthly occurrences showed a higher per cent above the average than below, and each of these has been underscored in Table 2.

Table 2--Frequency of monthly precipitation in terms of the average

(60-year records)

Month	Atlantic City			Duluth			Galveston			Seattle		
	Below average	Above average	Aver-age	Below average	Above average	Aver-age	Below average	Above average	Aver-age	Below average	Above average	Aver-age
January	34	26		34	26		35	25		30	29	1
February	33	27		35	25		36	24		29	31	
March	34	26		33	27		37	23		37	23	
April	34	26		35	24	1	37	23		34	26	
May	27	33		32	28		29	31		34	25	1
June	36	24		33	27		35	25		32	27	1
July	31	29		33	27		35	25		35	25	
August	38	22		32	28		36	24		35	24	1
September	36	24		32	27	1	38	22		30	30	
October	36	24		29	30	1	38	22		27	33	
November	40	20		34	26		32	28		33	27	
December	33	27		37	23		37	23		37	22	1
Totals	412	308		399	318	3	425	295		393	322	5
Per cent	57	43		56	44		59	41		54	45	1

Table 3--Monthly precipitation-averages and medians
(60-year records)

Station	Average	Median	Difference	Average	Median	Difference	Average	Median	Difference	Average	Median	Difference
		January			February			March			April	
Portland (Maine)	4.20	3.90	0.30	4.43	3.93	0.50	4.04	3.90	0.14	3.51	3.00	0.51
Cleveland	2.55	2.30	0.25	2.43	2.00	0.43	2.70	2.45	0.25	2.47	2.20	0.27
Atlantic City	3.48	3.25	0.23	3.31	3.10	0.21	3.62	3.50	0.12	3.14	2.95	0.19
Atlanta	4.85	4.25	0.60	4.76	4.45	0.31	5.36	4.30	1.06	3.85	3.32	0.53
Key West	1.86	1.44	0.42	1.41	1.00	0.41	1.48	0.94	0.54	1.33	0.90	0.43
Duluth	1.01	0.80	0.21	1.03	0.81	0.22	1.49	1.33	0.16	2.07	1.80	0.27
St. Louis	2.34	1.88	0.46	2.56	2.50	0.06	3.38	2.95	0.43	3.81	3.25	0.56
Galveston	3.56	2.95	0.61	2.91	2.60	0.31	2.71	2.04	0.67	3.12	2.46	0.66
Bismarck	0.45	0.31	0.14	0.45	0.35	0.10	0.92	0.80	0.12	1.52	1.35	0.17
Denver	0.39	0.28	0.11	0.56	0.46	0.10	1.04	0.92	0.12	2.06	1.70	0.36
El Paso	0.44	0.33	0.11	0.40	0.20	0.20	0.33	0.24	0.09	0.26	0.09	0.17
Salt Lake City	1.33	1.27	0.06	1.45	1.27	0.18	1.92	1.74	0.18	1.98	1.81	0.17
Seattle	4.95	4.92	0.03	3.76	3.79	-0.03	3.12	2.67	0.45	2.31	2.00	0.31
San Francisco	4.48	3.75	0.73	3.63	3.00	0.63	3.02	2.79	0.23	1.51	1.02	0.49
		May			June			July			August	
Portland (Maine)	3.31	3.00	0.31	3.28	2.80	0.48	3.05	2.93	0.12	3.01	2.85	0.16
Cleveland	3.01	2.80	0.21	3.05	2.55	0.50	3.41	3.20	0.21	2.77	2.46	0.31
Atlantic City	3.01	3.22	-0.21	3.11	2.65	0.46	3.77	3.65	0.12	4.52	3.90	0.62
Atlanta	3.47	3.20	0.27	3.81	3.25	0.56	4.58	4.20	0.38	4.17	3.75	0.42
Key West	3.57	3.20	0.37	4.46	3.30	0.16	3.34	3.00	0.34	4.57	4.30	0.27
Duluth	3.14	2.90	0.24	3.81	3.71	0.10	3.64	3.46	0.18	3.12	3.03	0.09
St. Louis	4.34	3.80	0.54	3.82	3.50	0.32	2.98	2.70	0.28	2.99	2.40	0.59
Galveston	3.39	3.24	0.15	3.88	3.12	0.76	3.64	3.10	0.54	4.22	3.70	0.52
Bismarck	2.36	2.26	0.10	3.26	2.80	0.46	2.28	2.03	0.25	1.78	1.60	0.18
Denver	2.36	2.25	0.11	1.13	1.00	0.13	1.58	1.32	0.26	1.45	1.32	0.13
El Paso	0.35	0.10	0.25	0.62	0.43	0.19	1.81	1.41	0.40	1.62	1.36	0.26
Salt Lake City	1.80	1.77	0.03	0.78	0.55	0.23	0.53	0.42	0.11	0.87	0.73	0.14
Seattle	1.83	1.62	0.21	1.40	1.33	0.07	0.63	0.45	0.18	0.70	0.45	0.25
San Francisco	0.74	0.35	0.39	0.18	0.04	0.14	0.01	0.01	0.00	0.01	0.01	0.00
		September			October			November			December	
Portland (Maine)	3.26	2.75	0.51	3.09	3.00	0.09	3.36	3.15	0.21	4.05	4.00	0.05
Cleveland	3.18	2.74	0.44	2.67	2.30	0.37	2.61	2.45	0.16	2.41	2.10	0.31
Atlantic City	3.05	2.60	0.45	3.12	2.75	0.37	2.85	2.43	0.42	3.85	3.62	0.23
Atlanta	3.16	2.80	0.36	2.70	2.25	0.45	3.08	2.95	0.13	4.75	4.00	0.75
Key West	6.52	5.57	0.95	6.17	4.70	1.47	2.17	1.45	0.72	1.70	1.00	0.70
Duluth	3.32	3.21	0.11	2.32	2.33	-0.01	1.50	1.30	0.20	1.14	0.91	0.23
St. Louis	3.46	3.00	0.46	2.72	2.30	0.42	2.83	2.60	0.23	2.21	2.02	0.19
Galveston	5.39	4.00	1.39	4.13	2.94	1.19	3.40	2.85	0.55	3.77	3.06	0.71
Bismarck	1.29	0.96	0.33	0.95	0.86	0.09	0.56	0.40	0.16	0.56	0.42	0.14
Denver	0.92	0.75	0.17	1.03	0.82	0.21	0.60	0.54	0.06	0.71	0.63	0.08
El Paso	1.24	0.98	0.26	0.79	0.50	0.29	0.49	0.34	0.15	0.51	0.33	0.18
Salt Lake City	0.90	0.61	0.29	1.41	1.28	0.13	1.34	1.25	0.09	1.41	1.30	0.11
Seattle	1.74	1.74	0.00	2.80	3.03	-0.23	4.83	4.65	0.18	5.68	5.15	0.53
San Francisco	0.37	0.14	0.23	1.00	0.57	0.43	2.32	1.58	0.74	3.89	3.23	0.66

Enough data and specific cases have been cited from our climatological records to justify the statement that averages fail to express the snowfall- and precipitation-normals. Statisticians recommend the use of the median, mode, geometric mean, and harmonic mean as possible substitutes for the average, when the average is unsatisfactory.

The geometric and harmonic means are excellent methods for computing averages but they are as impractical as the curve-fitting methods used by statisticians. They become too involved mathematically for long series that are constantly changing.

This leaves the median and mode as possible substitutes. The median is the center value of a series arranged in its numerical sequence, that is, the median of any frequency-distribution has an equal number of occurrences below it as above it. The mode is the value in a series that has the greatest number of occurrences and around which a majority of the terms cluster. It is the most dominant term of a series, such as the most common age of a graduating class. Occasionally a series has more than one mode and it is possible for a series to have no visual evidence of a mode. The application of this method is best suited for frequency-distributions that are symmetrical in form.

Its application to our climatological records was found objectionable. Many records of precipitation and snowfall showed no visible signs of a mode even after using whole-inch intervals for constructing the frequency-distribution curves. The summer months at all the stations were without definite modes. This was especially noticeable for those stations subject to tropical and cloudburst types of storms. The record at St. Louis was used to make comparative studies from 25 years to 100 years. In several of the months no definite modes were apparent until 75 and 100 years of record were used. This would indicate that very long records should be used to obtain dependable modes. Since this is the exception rather than the rule for most of our climatological data, the method has little value for determining normals.

Table 4--Comparison of annual precipitation-averages and medians

(60-year records)

Station	Sum of monthly medians	Annual median	Annual average	Excess of annual average
Portland (Maine)	39.21	41.43	42.59	1.16
Cleveland	29.54	33.26	33.26	None
Atlantic City	37.62	39.00	40.83	1.83
Atlanta	42.72	48.40	48.54	0.14
Key West	30.80	38.30	38.58	0.28
Duluth	25.59	27.66	27.59	-0.07
St. Louis	32.92	37.37	37.44	0.07
Galveston	36.04	42.50	44.12	1.62
Bismarck	14.14	16.00	16.38	0.38
Denver	11.99	14.27	13.83	-0.44
El Paso	6.31	8.21	8.85	0.64
Salt Lake City	14.00	15.83	15.72	-0.11
Seattle	31.80	33.14	33.75	0.61
San Francisco	16.57	20.41	21.24	0.83

The positions of the median and the average were compared for all the records examined. The difference varied from a few hundredths of an inch to nearly two inches. Extreme variations were conspicuous among those months subject to abnormal climatological conditions. A striking example was found at Galveston for the month of October, in which the rainfall in 1924 was only 0.03 inch, and the next year 17.34 inches, just 578 times as much. The effect of a few of these high values during the 60-year record made the average 1.19 inches greater than the median value. September showed an even greater discrepancy, 1.39 inches.

Table 3 is a tabulation of the monthly averages and medians of precipitation for the 14 stations previously examined. The tabulation shows only four instances where the median was greater than the average and three instances when they were equal. The inconsistency between the monthly averages and medians varied from zero to 1.47 inches. More pronounced discrepancies were found during the summer and fall months. One must not lose sight of the true significance shown by Table 3, in that a small difference between the average and median for a dry month may represent a considerable portion of the amount that normally falls during the month. For instance, the average precipitation at El Paso for the month of May was 0.35 inch and the median was 0.10 inch. The difference of 0.25 inch, although numerically small, represents 250 per cent of the normal precipitation. In cases similar to this the arithmetical average grossly exaggerates the normal expectancy.

The maximum difference between the average and the median was found at Key West for the month of October, when the difference was 1.47 inches. In view of these statistics, the use of median for expressing a monthly normal seems more desirable.

The annual averages of snowfall and precipitation examined showed a favorable correlation with the medians. However, it was discovered that the annual median should not be determined by summing up the individual monthly medians. This procedure gives an annual median much too small. Table 4 is a tabulation of the annual averages and medians of precipitation for all the stations previously reviewed for monthly data.

The temperature-records for nine stations selected at random over the country indicate that the arithmetical average makes an excellent normal. It was found that the monthly temperatures were not consistently lower or higher than the average and the difference between the medians and averages was insignificant. Out of 2,160 monthly means examined, 1,056 were above the average and 1,069 were below the average, with 35 just average. This would indicate that there is little room for improvement and that the average serves adequately for denoting temperature-normals.

The frequency-distribution for most of the records were symmetrical and modes were very distinct. This accounts for the small discrepancies between the medians and averages.

The conclusions drawn from this review of the climatological records are: The arithmetical average fails to give representative value for monthly normals of snowfall and precipitation but serves adequately for temperature-normals. Of the methods that might serve as a possible substitute for denoting normals, the median is by all means the most favorable. It gives the most practical value for expressing the normal, and of all the possible alternates it was the least affected by irregular frequency-distributions. In case the median should be used for expressing the normal, it should be made explicit that the annual normals for snowfall and precipitation must be ascertained from the annual records and not from the summation of the monthly medians.

U. S. Engineer Office,
Portland, Oregon

DISCUSSION

H. T. GISBORNE (U. S. Forest Service, Missoula, Montana)--Mr. Gisborne described specific cases of erroneous practical conclusions resulting from use of the mathematical average as an index of "normal." He cited dictionary definitions that "normal" means usual and most common, which is the 50/50 probability. He then offered a resolution advocating the future use of the median instead of the average in all publications and releases of precipitation-normals.
J. Cecil Alter seconded the motion to have this resolution considered and acted upon by a Committee of the Section of Hydrology, American Geophysical Union.

It was moved, seconded, and passed that the Chair appoint a Committee. Mr. Stevens appointed Professor Phil E. Church, Chairman, Edward L. Wells, and Professor H. P. Boardman.

[Note: For index of names and of subjects in Part III-C, see page 1060 and following.]

MINUTES OF SEATTLE MEETING

REPORT, CHAIRMAN OF EXECUTIVE COMMITTEE, WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

A meeting of the South Pacific Area of the Western Interstate Snow-Survey Conference was held at Stanford University, California, January 12, 1940, at which time your Chairman reported on two meetings held in December, 1938. One of these meetings, that at Los Angeles, was attended by 25 persons and the other, at Spokane, by 33. Both were interesting meetings, the one at Spokane, held in connection with a session of the Northwest Scientific Association, being the first formal meeting of the Western Interstate Snow-Survey Conference to be held in its northern Areas.

The Stanford dinner meeting was attended by 63 persons, most of whom remained until near the midnight hour, the explanation being that it was the occasion of the formulation of the By-Laws of this organization. These By-Laws were later submitted to the membership for approval, the balloting being kindly conducted by Fred H. Paget of the California Cooperative Snow-Surveys and a member of the Executive Committee.

The canvassing of the ballots was accomplished March 12. Three hundred and ten ballots were sent out and 110 were returned (one blank and 109 yes, nine of the yes votes lacking the requested signature of the voter on the envelope). A recent statement from Mr. Paget tells of several late votes being received, none of these being no, so the adoption can be said to be unanimous. I do not think it advisable to take time to read from the By-Laws at this time. New members who have not received copies will no doubt be supplied later.

The selection of members of your next Executive Committee is now under way and this is also being conducted by Mr. Paget as he has available stenographic help and facilities for making multiple copies of necessary circulars, etc.

Most of you are aware that the moving spirit of this organization is Dr. Church and that he does move. He and his assistant, Carl Elges, and their efficient office assistants and also this year Fred Paget, are the ones who deserve the main credit for the accomplishments of the past two years.

Many of you have received printed copies of the Snow-Survey Conference papers and also the hydrological papers presented at the Los Angeles and Spokane meetings. The financing of the printing of these papers and the publication and distribution of the reprints have been accomplished mainly by the purchase of multiple copies of the reprints by numerous cooperating organizations. A financial statement follows.

Receipts		
On hand June 30, 1939	$89.69	
Interest	0.55	
Collections for reprints of Western Interstate Snow-Survey Conference Proceedings and Report of American Geophysical Union's Committee on Snow	765.00	
Advanced by Dr. Church	315.00	$1,170.24
Expenditures		
Printing 2,500 reprints of Western Interstate Snow-Survey Conference Proceedings	$565.00	
Printing 1,500 copies of Report of American Geophysical Union's Committee on Snow	140.00	
Handling charges in Washington	49.50	
Stamps, express, and postal cards	101.90	
Printing of programs for Stanford Meeting	5.22	
Repaid to Dr. Church	290.00	
Deposited in Bank	18.62	$1,170.24

The discussion of the financing of the publication of the papers of the Stanford Meeting and this Seattle Meeting is in order this evening. It is my understanding that the papers of both the Snow-Survey Conference and the Section of Hydrology of the American Geophysical Union presented at the Stanford Meeting are to be published in one separate volume of the Transactions of 1940 of the American Geophysical Union and that the same arrangement is to be carried out for the papers presented at this Seattle Conference. If reprints are wanted of the Snow-Survey Conference papers, it will be cheaper to order extra copies of this volume than to require that the snow-survey papers be reprinted separately from the hydrological papers.

Final proof for the Stanford Snow-Survey Conference papers has been checked and forwarded to Washington.

A decision must be made soon on the number of extra copies to be ordered, if any, and the same kind of decision should be made relative to the papers presented at this Seattle Meeting if it is practicable at this time.

In accordance with a provision of the By-Laws for securing new members whose applications are approved by the Executive Committee, our membership has been increased by about 200 within the last two or three months but no dues or membership-fees are involved. This brings our total membership to about 500.

A complete list of those attending the Conference at Seattle is included in Appendix A which follows the Minutes of the Regional Meeting at Seattle of the Section of Hydrology of the American Geophysical Union prepared by Secretary West [pp. 1054-1055].

The results of elections to the new Executive Committee for the period 1940 to 1942 are given in the attached list. As the mail-ballots for the election were not all received, and the choice of the Committee for its Chairman was not made, before adjournment of the Conference, I could not have the privilege of presenting my successor as General Chairman, namely, Fred Paget, at the Conference.

H. P. Boardman, Chairman

PERSONNEL, EXECUTIVE COMMITTEE, WESTERN INTERSTATE SNOW-SURVEY CONFERENCE, 1940-42

Nominations were for Regions but elections were by the whole Conference. The Regional Chairmen were elected on a preferential ballot designating first, second, and third choices.

FRED PAGET, General Chairman

North Continental Divide Area

O. W. MONSON (Chairman), Irrigation Engineer, Montana State College, Agricultural Experiment Station, Bozeman, Montana
JAMES C. MARR, Irrigation Engineer, Soil Conservation Service, Boise, Idaho
H. T. GISBORNE, In charge of Forest Protection, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana
LYNN CRANDALL, Watermaster, Idaho Water District No. 36, U. S. Geological Survey, Idaho Falls, Idaho
WALTER E. JOHNSON, In charge of snow-surveys in Chelan and Spokane basins, Washington Water Power Company, Spokane, Washington

South Continental Divide Area

GEORGE D. CLYDE (Chairman), Dean of Engineering and Mechanic Arts, Utah State Agricultural College, Logan, Utah
R. L. PARSHALL, Senior Irrigation Engineer, Soil Conservation Service, Fort Collins, Colorado
J. CECIL ALTER, Meteorologist-in-Charge, U. S. Weather Bureau, Salt Lake City, Utah
HARRY L. POTTS, Special Engineer, Denver Water Board, Denver, Colorado
ASHTON R. CODD, Hydrologic Supervisor, U. S. Weather Bureau, Salt Lake City, Utah (now Portland, Oregon)

North Pacific Coast Area

GEORGE G. WEST (Chairman), Hydrologist, U. S. Army Engineers, Portland, Oregon
R. A. WORK, Associate Irrigation Engineer, Soil Conservation Service, Medford, Oregon

North Pacific Coast Area--Concluded

R. C. FARROW, Chief Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia
G. H. CANFIELD, District Engineer, U. S. Geological Survey, Portland, Oregon
PHIL E. CHURCH, Assistant Professor of Geography and Meteorology, University of Washington, Seattle, Washington

South Pacific Coast Area

FRED H. PAGET (Chairman), Associate Hydraulic Engineer, Division of Water Resources, California State Department of Public Works, Sacramento, California
H. P. BOARDMAN, Civil Engineer, 735 West Street, Reno, Nevada
W. A. LANG, Chief Hydrographer, Southern California Edison Company, Los Angeles, California
JAMES E. JONES, Civil Engineer, Los Angeles Department of Water and Power, Los Angeles, California
JOSEPH KITTREDGE, JR., Professor of Forestry and Forest Ecologist, Agricultural Experiment Station, University of California, Berkeley, California

MINUTES OF THE REGIONAL MEETING OF THE SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION, AT SEATTLE, WASHINGTON, JUNE 20-21, 1940

On the afternoon of June 20, 1940, the sessions were held jointly with the Western Interstate Snow-Survey Conference.

Papers were presented by their authors, as published in these Transactions, in accordance with the published program with the following exceptions: The paper by H. B. Atkinson and Clyde E. Bay was presented by Dr. J. E. Church; the synopsis only of the paper by H. P. Gillette was read by George G. West; the paper by D. B. Freeman was presented by O. W. Monson. At the luncheon on June 21, 1940, an extremely interesting and instructive sound-film, "Story of electric service," was presented by Walter E. Johnson of the Washington Water Power Company, Spokane, Washington. Many members of the Western Interstate Snow-Survey Conference and American Meteorological Society also witnessed this film.

Forty-nine persons, as listed in Appendix A, took part in the Meeting.

After the presentation of the last paper on the afternoon of June 21, 1940, there was open discussion of medians versus averages. A Resolution was offered by H. T. Gisborne as follows:

RESOLUTION ON THE USE OF THE MEDIAN INSTEAD OF THE AVERAGE (submitted by H. T. Gisborne, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana)

WHEREAS, The expression of departure from normal for any meteorological element is an index of widespread scientific, practical, and popular application and interest, and

WHEREAS, The significance of such departures lies in the implication that the condition measured has differed from the usual or most common condition, and

WHEREAS, An examination of the precipitation-records for 14 stations well distributed throughout the United States has been made by G. W. Mindling of the United States Weather Bureau and this study has shown that for 59 per cent of the 10,080 station-months' records examined the arithmetical average heretofore used as the expression of normal is not as accurate and dependable as the median in showing the amount of (monthly) rainfall that approximates the most common amount, therefore be it

RESOLVED, That the North Pacific and North Continental Divide Areas of the Section of Hydrology of the American Geophysical Union recommend that, in future hydrologic studies, normals of precipitation be defined by the median instead of the arithmetical average, and be it further

RESOLVED, That copies of this resolution be furnished to all other divisions of the Section of Hydrology with the request that they examine the procedure here recommended and take definite action either for or against this proposal.

It was moved, seconded, and passed that the Resolution be referred to a Committee for an early report. It was also moved, seconded, and passed that the Chair appoint the Committee, whereupon J. C. Stevens appointed Professor Phil E. Church (Chairman) of the University of Washington at Seattle, Washington, Edward L. Wells, Meteorologist of the United States Weather Bureau at Portland, Oregon, and Professor H. P. Boardman of 735 West Street at Reno, Nevada.

The meeting adjourned at 5:40 p.m.

(Signed) Geo. G. West, Secretary

APPENDIX A--RECORD OF 80 MEMBERS AND GUESTS WHO ATTENDED THE JOINT REGIONAL MEETINGS OF THE SECTION OF HYDROLOGY, THE WESTERN INTERSTATE SNOW-SURVEY CONFERENCE, AND THE AMERICAN METEOROLOGICAL SOCIETY AT SEATTLE, WASHINGTON, JUNE 19-21, 1940

[1 = Session of Section of Hydrology, June 21, 1940; 2 = sessions of Western Interstate Snow-Survey Conference, June 19 and 20, 1940; 3 = joint session of Western Interstate Snow-Survey Conference, Section of Hydrology, and American Meteorological Society, June 20, 1940 (including joint dinner meeting)]

Thomas C. Adams (2,3), Engineering College, University of Utah, Salt Lake City, Utah
J. M. Allison (1,2,3), U. S. Engineer Office, Portland, Oregon
J. Cecil Alter (1,2,3), U. S. Weather Bureau, Salt Lake City, Utah
I. E. Anderson (3), U. S. Geological Survey, Tacoma, Washington
Merrill Bernard (2,3), U. S. Weather Bureau, Washington, D. C.
J. Bjerknes (3), U. S. Weather Bureau, Seattle Airport, Seattle, Washington
H. P. Boardman, (1,2,3), Civil Engineer, 735 West Street, Reno, Nevada
G. L. Bodhaine (1), U. S. Geological Survey, Tacoma, Washington
W. H. Bolles (1,2,3), Pacific Northwest Forest Experiment Station, Portland, Oregon
J. P. Bonner (1), Soil Conservation Service, University of Idaho, Moscow, Idaho
George H. Canfield (1,3), U. S. Geological Survey, Portland, Oregon
Archer B. Carpenter (3), U. S. Weather Bureau, Seattle Airport, Seattle, Washington
W. J. Centen (3), U. S. Weather Bureau, Spokane, Washington
J. E. Church (1,2,3), Nevada Agricultural Experiment Station, Reno, Nevada
Phil E. Church (1,2,3), Assistant Professor of Meteorology and Geography, University of Washington, Seattle, Washington
George D. Clyde (1,2,3), Utah State Agricultural College, Logan, Utah
Ashton R. Codd (1,2,3), U. S. Weather Bureau, Portland, Oregon
Chas. A. Connaughton (2), Director, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado
L. H. Daingerfield (3), U. S. Weather Bureau, Los Angeles, California
John C. Eberhardt (3), U. S. Weather Bureau, Fairbanks, Alaska
Carl Elges (1,2,3), Nevada Agricultural Experiment Station, Reno, Nevada
H. A. Elliott (3), U. S. Weather Bureau, Seattle, Washington
R. C. Farrow (1,2,3), Water Rights Branch, Victoria, B. C.
Elmer Fisher (1,2,3), U. S. Weather Bureau, Portland, Oregon
Dwayain K. Ford (1,2,3), U. S. Engineer Office, Seattle, Washington
Maurice A. Garbell (3), Boeing School of Aeronautics, United Airlines, Oakland, California
A. J. Gilardi (1), U. S. Engineer Office, Galveston, Texas
H. T. Gisborne (1,2,3), U. S. Forest Service, Missoula, Montana
Walter J. Herz (1,2,3), Snow-Surveyor, Sierra Pacific Power Company, Reno, Nevada
D. E. Hilton (1,2,3), U. S. Weather Bureau, Havre, Montana
George F. Hopkins (1,2,3), Associate Engineer, U. S. Engineer Office, Seattle, Washington
C. M. Howard (1), 4207 Bagley Avenue, Seattle, Washington
Woodrow C. Jacobs (3), U. S. Weather Bureau, Pomona, California
R. Jaren (1,2,3), U. S. Engineer Office, Portland, Oregon
J. E. Jennin (3), U. S. Weather Bureau, Seattle, Washington
Arthur Johnson (1,3), U. S. Geological Survey, Tacoma, Washington
Walter E. Johnson (1,2,3), Washington Water Power Company, Spokane, Washington
Joseph Kittredge, Jr. (2), Professor of Forestry, University of California, Berkeley, California
Marguerite E. Kittredge (2,3), Duluth Jr. College, Duluth, Minnesota
N. E. Koski (3), Graduate Student, University of Washington, Seattle, Washington
P. H. Kutschenreuter (3), U. S. Weather Bureau, Billings, Montana
Norbert Leupold (1,2,3), U. S. Engineer Office, Portland, Oregon
John B. Lightfoot (1,2,3), U. S. Weather Bureau, Seattle, Washington
David O. Lind (2), Seattle, Washington
J. D. MacVicar (2), Maintenance Engineer, Department of Highways, State of Washington, Olympia, Washington
Frank J. Marks (1,2,3), U. S. Engineer Office, Portland, Oregon
James C. Marr (1,2,3), Soil Conservation Service, Box 835, Boise, Idaho
W. E. Maughan (2,3), Associate Meteorologist, U. S. Weather Bureau, Helena, Montana
Fred Merryfield (1), Oregon State College, Corvallis, Oregon
O. W. Monson (1,2,3), Montana Experiment Station, Bozeman, Montana
S. M. Munson (1,2,3), California Forest Experiment Station, University of California, Berkeley, California
M. L. Nelson (1,2,3), U. S. Engineer Office, 828 Pittock Block, Portland, Oregon

H. Dean Parry (3), U. S. Weather Bureau, Salt Lake City, Utah
R. L. Parshall (1,2,3), Division of Irrigation, Soil Conservation Service, Fort Collins, Colorado
Walter J. Parsons, Jr. (1,2,3), U. S. Engineer Office, Sacramento, California
Clarence Pedersen (1,2,3), U. S. Engineer Office, Portland, Oregon
K. N. Phillips (1,3), U. S. Geological Survey, Portland, Oregon
R. Rhaton (3), U. S. Weather Bureau, Seattle, Washington
Paul A. Rosholt (1), U. S. Engineer Office, Seattle, Washington
Otto N. Rugen (1,3), U. S. Engineer Office, Los Angeles, California
Vernon W. Rupp (1,2,3), Hydrologic Supervisor, U. S. Weather Bureau, San Francisco, California
Sidney M. Serebreny (3), University of Minnesota, Minneapolis, Minnesota
T. Edward Stephens (2), Graduate Student, University of Washington, Seattle, Washington
J. C. Stevens (1,2,3), Consulting Engineer, Spalding Building, Portland, Oregon
H. R. Stevens (1), Bonneville Project, Portland, Oregon
Harry E. Torbitt (3), U. S. Weather Bureau, Seattle, Washington
R. G. Tyler (1,3), University of Washington, Seattle, Washington
B. M. Varney (3), University of California at Los Angeles, California
F. M. Veatch (1,3), U. S. Geological Survey, Tacoma, Washington
H. M. Wanser (1,2,3), Soil Conservation Service, Spokane, Washington
R. D. Waterhouse (2), Regional Engineer, National Park Service, San Francisco, California
Harry E. Weirauch (3), U. S. Weather Bureau, Seattle, Washington
Edward L. Wells (1,2,3), U. S. Weather Bureau, Portland, Oregon
George G. West (1,2,3), U. S. Engineer Office, Portland, Oregon
Harvey O. Westby (1,3), U. S. Engineer Office, Seattle, Washington
J. H. Whipple (3), U. S. Weather Bureau, Pendleton, Oregon
Philip Williams, Jr. (3), U. S. Weather Bureau, Seattle, Washington
R. A. Work (1,2,3), Associate Irrigation Engineer, Soil Conservation Service, Medford, Oregon
A. A. Young (1), Soil Conservation Service, Pomona, California
C. N. Young (2,3), Irrigation Engineer, Burns, Oregon

INDEX FOR PART III

IDEX OF NAMES FOR PART III-A

Perry Byerly, 815
Maurice Ewing, 796
N. H. Heck, 826
Chester R. Longwell, 783
E. B. Mathews, 792
Wilbur A. Nelson, 786
Paul A. Smith, 786
Harlan True Stetson, 822
C. H. Swick, 801
W. T. Thom, Jr., 825
A. C. Veatch, 786
George Prior Woollard, 808

INDEX OF SUBJECTS FOR PART III-A

- Appalachia
  - Cambrian, 788
  - Canadian, 788
  - Devonian, 789
  - Eocene, 794
  - Jurassic, 791
  - Lower Cretaceous, 791
  - Miocene, 794
  - Mississippian, 790
  - Oligocene, 794
  - Ordovician, 789
  - Ozarkian, 788
  - Pennsylvania, 790
  - Permian and Triassic, 790
  - Pleistocene, 794
  - Pliocene, 794
  - Pre-Cambrian, 786
  - Silurian, 789
  - Upper Cretaceous, 793
- Appalachia, topography of former continent of (from geologic evidence), 786
- Areal geologic sketch-map of Virginia, 811
- Atlantic Coastal Plain seismic studies, historic background of, 796

- Basement-complex, seismic refraction-method in tracing surface of, 797
- Basement-map of Baltimore area showing topography of portion of buried land-surface of Appalachia, 792
- Brown gravity-apparatus, 801

- Cambrian Appalachia, 788
- Canadian Appalachia, 788
- Collaborative research in further study of continental borders, 825
- Configuration and slope of surface of basement-complex beneath Virginia Coastal Plain, contour-map showing, 811
- Crustal structure of continental borders, gravitational determination of deep-seated
  - Observations and methods, 801
  - Structural interpretation of gravity-observations, 808
- Crustal structure, relative rôles of geology and geophysics in determining, 783
- Crustal structure, time-problem in geophysical study of, 822

- Deep-seated crustal structure in California, seismic determination of, 815
- Deep-seated crustal structure of continental borders, gravitational determination of
  - Observations and methods, 801
  - Structural interpretation of gravity-observations, 808
- Devonian Appalachia, 789
- Distribution of gravity-stations in United States as of December 1938, 802

- Eocene Appalachia, 794
- Epicenters of certain recent earthquakes with respect to northern portions of San Andreas Rift, 819

- Faulting off coast of northern California, 819

- Geologic evidence of topography of former continent of Appalachia, 786
- Geologic, seismic, and gravitational profiles across Virginia Piedmont, Coastal Plain, and Continental Shelf, 813
- Geology and geophysics in determining crustal structure, 783
- Geophysical study of crustal structure, time-problem in, 822
- Granitic root, idealized cross-section through Sierra Nevada showing postulated, 818
- Gravitational determination of deep-seated crustal structure of continental borders
  - Observations and methods, 801
  - Structural interpretation of gravity-observations, 808
- Gravity-apparatus, Brown, 801
- Gravity-profiles after isostatic reduction, 807
- Gravity-profiles, gravity-stations, and iso-anomaly lines in Florida, 806
- Gravity-sections, 814
- Gravity-stations and iso-anomaly lines in southern New England and middle Atlantic areas, 804, 805
- Gravity-stations, gravity-profiles, and iso-anomaly lines in Florida, 806
- Gravity-stations in United States as of December 1938, distribution of, 802
- Gravity-stations in Virginia and North Carolina, locations of, 803

- Historic background of Atlantic Coastal Plain seismic Studies, 796

- Idealized cross-section through Sierra Nevada showing postulated granitic root, 818

Introduction, 783
Iso-anomaly lines and gravity-stations in southern New England and middle Atlantic areas, 804, 805
Iso-anomaly lines, gravity-stations, and gravity-profiles in Florida, 806
Isostatic reduction, gravity-profiles after, 807

Jurassic Appalachia, 791

Land-surface of Appalachia, basement-map of Baltimore area showing topography of portion of buried, 792
Layering of crust from travel-time data, graph showing method of interpreting, 816
Location of seismic refraction-measurements in Atlantic Coastal Plain in 1938, 799
Locations of gravity-stations in Virginia and North Carolina, 803
Lower Cretaceous Appalachia, 791

Mapping submarine valleys of Atlantic, 786
Method of interpreting layering of crust from travel-time data, graph showing, 816
Miocene Appalachia, 794
Mississippian Appalachia, 790

Northern portion of San Andreas Rift active in earthquake of 1906, sketch-map showing, 820

Observations and methods in gravitational determination of deep-seated crustal structure of continental borders, 801
Oligocene Appalachia, 794
Opportunities for collaborative research in further study of continental borders, 825
Ordovician Appalachia, 789
Ozarkian Appalachia, 788

Pennsylvania Appalachia, 790
Permian and Triassic Appalachia, 790
Pleistocene Appalachia, 794
Pliocene Appalachia, 794
Pre-Cambrian Appalachia, 786
Present position of former topographic surface of Appalachia (from seismic evidence), 796
Present regional configuration of pre-Eocene land-surface and former land-surface of Appalachia, sketch-map showing, 793

Relation of gravity-anomalies to lithologic variations in basement-complex, 810
Relation of gravity-anomalies to regional geologic structure in eastern United States, 809
Relation of gravity-trends to geologic structure in eastern United States, sketch map, 810
Relative rôles of geology and geophysics in determining crustal structure, 783

San Andreas Rift, epicenters of certain recent earthquakes with respect to northern portions of, 819
San Andreas Rift, sketch-map of northern portion of, active in earthquake of 1906, 820
Seismic determination of deep-seated crustal structure in California, 815
Seismic evidence of topographic surface of present position of Appalachia, 796
Seismic measurements already made or projected, 798
On land areas, 798
Shallow-water measurements, 798
Deep-water measurements, 800
Seismic refraction-measurements in Atlantic Coastal Plain in 1938, location of, 799
Seismic refraction-method in tracing surface of basement-complex, 797
Seismograms obtained in Atlantic Coastal Plain with geophones, 798
Sierran root, 818
Sierran root, map indicating position and areal outline of, 818
Silurian Appalachia, 789
Sketch-map showing present regional configuration of pre-Eocene land-surface and former land-surface of Appalachia, 793
Structural interpretation of gravity-observations in gravitational determination of deep-seated crustal structure of continental borders, 808
Submarine valleys of Atlantic, mapping of, 786
Surface and subsurface exploration of continental borders, symposium on, 783
Symposium on the surface and subsurface exploration of continental borders, 783

Time-problem in geophysical study of crustal structure, 822
Topographic surface of Appalachia, present position of (from seismic evidence), 796
Topography of former continent of Appalachia (from geologic evidence), 786
Typical travel-time (Parkfield earthquake, June 7, 1934), 817

Uplift and westward tilting of Appalachia during Paleozoic followed by eastward tilting in Post-Jurassic, diagram of, 787
Upper Cretaceous Appalachia, 793
Use of seismic refraction-method in tracing surface of basement-complex, 797

INDEX OF NAMES FOR PART III-B

J. Cecil Alter, 892, 925, 935
H. B. Atkinson, 935
Clyde E. Bay, 935
Paul L. Bean, 835, 949
Paul Webster Bean, 916
Frederick A. Bendtsen, 916
Merrill Bernard, 915, 935
J. Bjerknes, 979
H. P. Boardman, 870, 878, 1052
H. H. Burt, 951
J. J. Capello, 830
John Chatillon and Sons, 908, 909, 910
J. E. Church, 835, 858, 874, 879, 901, 909,
  910, 916, 919, 925, 932, 935, 953, 973
Phil E. Church, 928, 935
George D. Clyde, 871
Ashton R. Codd, 913, 951
E. H. Collins, 887
Harold Conklin, 980
Chas. A. Connaughton, 920
Philip S. Cowgill, 904
J. Carlisle Crouch, 925
Edwin S. Cullings, 949
Carl Elges, 874, 904, 909, 911, 980
R. H. Elliott, 953, 956, 968, 969
R. C. Farrow, 892, 925, 987
Lawrence C. Fisher, 887
J. A. Fleming, 830
D. B. Freeman, 986
H. T. Gisborne, 925
J. W. Green, 830
L. Standish Hall, 855, 968
W. C. Hendrix, 830
Walter Herz, 979
Eric Hinton, 855
Walter E. Johnson, 984
Kirby Lithographic Co., Inc., 830
J. D. MacVicar, 932
James C. Marr, 980, 984
W. T. McFarlane, 988
Fred D. McLaren, 951
W. W. McLaughlin, 920, 980
O. W. Monson, 920, 980, 986
Ukitiro Nakaya, 935
Walter J. Parsons, Jr., 951, 956, 970
Kenneth L. Roberts, 949
J. H. Ryan, 981
John T. Ryan, 902
John V. Salo, 858, 870, 992
W. E. Scott, 830
LeRoy K. Sherman, 969
W. F. Steiner, 830
J. C. Stevens, 905, 915, 973
Philip W. Thomas, 835, 847
E. M. Tucker, 904
William Tuller, 984
R. D. Waterhouse, 920
R. A. Work, 901, 920, 979, 981

INDEX OF SUBJECTS FOR PART III-B

Activities in snow-surveys, 920
Androscoggin, Merrimack, and Connecticut
  basins, map of, 836
Androscoggin River Drainage-Basin and snow-measuring stations in Maine and New Hampshire, 838, 839
Application of mean-elevation method, 864

Bow River Basin, 988
  Snow-surveys on, 990
British Columbia, accuracy of forecasts in, 987

Calcium chloride, problem of using in precipitation-gages, 911
Calcium-chloride solutions in operation of precipitation-gages, 913
Calculation of average water-content, 864
California cooperative snow-survey courses, Mokelumne River, 857
"Cesco" face-shields, 904
Chelan Basin snow-surveys
  Comparison of density in per cent, 890
  Comparison of water-content of snow, 889
  Computation of water in snow-storage, 890
Chelan Basin, snow-surveys of 1939, 887
Chelan Lake, forecast and runoff, 984
Coeur d'Alene Lake, forecast and runoff, 984
Contour drainage-basin map, Androscoggin River, 851, 852, 853
Corrections to precipitation-records for variation in altitude and slope-exposures, 850

Dinner meeting, 979

Equipment for snow-surveys, 892, 901
Executive Committee, Western Interstate Snow-Survey Conference
  Personnel, 1940-42, 1052
  Report of Chairman, 1051

Films: Formation of snow-crystals in the mountains and in the laboratory of Japan (sound), 935; Snow-surveying in the Cascades, 892; Snow-surveying in the Central Sierra (color), 979
Flood-peaks, relation of snow to maximum, 951, 953
Floods
  Desert, 967
  Humboldt of 1910, 966
  Of 1936, 846
  Of 1907, 1928, 1937, and 1940, 958
  Sacramento Basin, 1937, 959
  Tahoe-Truckee Basin, 958
Forecast and runoff, Lakes Coeur d'Alene and Chelan, 984
Forecasts
  In British Columbia, 987
  Upper Mississippi River at Fort Peck, 986
Forecast-system for power- and flood-warnings in Androscoggin River Basin, Maine, 835
Forecasting, 835
Forecasting equipment, 892
Forecasting in Humboldt Basin, Nevada, present trends in improving, 874
Forecasting runoff from snow-cover, soil-moisture studies as an aid in, 871
Forecasting runoff from snow-surveys, quantitative method of, 855

Frost-penetration .
  Conclusions on, 947
  Some factors affecting, 935

Highway snow-surveys, 932
Hydrograph, unit-, 969

Ice-crusts and snow-settling at Snoqualmie Pass, season of 1939-40, 928
Ice-gorging
  Effect of reservoir-operation, 975
  Ice-forming factor, 976
  Winter overflow on shallow streams, 973
Ice in northern streams of United States, 970
  Effect on river-flow characteristics, 971
  Behavior in mid-winter, 971
  Thawing of river, 972
Improvements of Tucker motor-sled, 902

Kootenay-Columbia basins, 987

Lake Chelan inflow and outflow, 891

Map of Western snow-survey systems, 874
Mean-elevation method, application of, 864
Members and guests attending joint Regional Meeting, Seattle, Washington, 1054
Merrimack River Drainage-Area, 861, 862
Missouri River, forecasts at Fort Peck for upper, 986
Mokelumne Watershed, estimate of total water-content of snow, April 1, 1938, 857
Mountain snow-survey: Its Genesis, Exodus, and Revelation, 892
Mount Rose snow-scale, tests of, 905

Nevada Cooperative Snow-Surveys, snow-survey courses, 876, 877
New England, snow-sampling equipment for, 916
Normals, 879

Okanagan Basin, 988

Pacific Northwest, accuracy of forecasts in, 988
Pemigewasset and Winnepesaukee Drainage-Areas, 861
Percentage-system of estimating water-supply from basins, 878
Powder-snow, difficulties in traversing, 902
Precipitation-data for Yakima Basin, 880, 881, 882
Precipitation-data to indicate effect of altitude and slope-exposure on annual precipitation, 848, 849
Precipitation-gages, calcium-chloride solutions in operation of, 913
Precipitation-gages, problem of using calcium chloride in, 911
Precipitation-variation as the latitude and elevation of recording stations vary, 847
Present trends in improving forecasting in Humboldt Basin, Nevada, 874
Problems in forecasting water-supplies, 920
Proposed snow-survey system for Yakima Basin, 878

Quantitative forecast-system for power- and flood-warning in the Androscoggin River Basin, Maine, 835
Quantitative forecast-system of runoff based on snow-surveys at the mean elevation of the snow-cover, 858
Quantitative method of forecasting runoff from snow-surveys, 855

Rainfall, effect on snow, 958
Rain-shadow, 956
Relation between elevation and area of Merrimack Basin, 863
Relation of elevation and water-content for 1939 snow-surveys of Merrimack Basin, 863, 864, 866
Relation of precipitation and runoff for Yakima Basin, 883
River-ice, thawing of, 972
Runoff from melting snow at Mokelumne gaging-station, 856

Saint Mary River Basin, 988
  Snow-surveys on, 989
Salt Lake City Area, comparison of precipitation and snow-survey values with subsequent stream-discharge, 896, 897, 898
Ski-etiquette and ski-safety, 925
Ski-safety and ski-etiquette, 925
Snoqualmie Pass, ice-crusts and snow-settling at, 928
Snow-activities, U. S. Park Service, 920
Snow-cohesion and snow-loads, plan for a study in estimating strength of roofs against snow-overload, 901
Snow-crystals, formation of in mountains and laboratory of Japan, a sound film, 935
Snow-density, 958
Snow, forecasting of stream-flow from melting, 935
Snow-measurements
  Equipment used in, 916
  Establishment of stations for, 916
  Experimental work, 918
  Procedure of, 917
Snow-melting, rate of, 958
Snow, relation to maximum flood-peak, 951, 953
Snow-research by Forest Service, 920
  Completed, 921
  Future of, 924
  In progress, 921
Snow-sampling equipment for granular and crusted snow in New England, 916
Snow-settling at Snoqualmie Pass, 928
Snow-shadow, 957
Snow-survey activities, 920
Snow-survey courses, Nevada Cooperative Snow-Surveys, 876, 877
Snow-survey data, 1939 and 1940, Pemigewasset and Winnepesaukee areas, 869
Snow-survey equipment, improvement of, 904
Snow-surveying, difficulties of, 992
Snow-surveying films
  In the Cascades, 892
  In Central Sierra (color), 979

Snow-surveys
  In Androscoggin River Basin, 835
  Of 1939 in Chelan Basin, 887
  On Bow River, 990
  On Saint Mary River Basin, 989
  Utilization of for storage-purposes, 843
  Utilization of in estimating floods, 845
Snow-types met in highway snow-surveys, 932
Soil-moisture-indicating device, 872
Soil-moisture studies as an aid in forecasting runoff from snow-cover, 871
Source of maximum floods, 956
Spring-balances, new by John Chatillon and Sons, 908
Standards and terminology for water-supply forecasts, 979
Stream-flow, forecasting of from melting snow, 935
Stream-forecasts in Montana, 986
Strength of roofs, estimating strength of against snow-load, 901

Temperature, depth, and water-content of snow at Aziscohos Dam, 840, 841
Trend of water-content of snow-covers, 865
Tucker motor-sled, 902

Unit-hydrograph, 969
Utilization of snow-surveys
  In estimating floods, 845
  For storage-purposes, 843

Watersheds, regional reports for northern, 981
Water-supplies, forecasting of, 920
Water-supply
  Boise River, Idaho, 984
  Forecast-accuracy, 979
  Oregon, 981
  Pacific Northwest, 988
  Standards and terminology, 979
Weighting of snow-survey data at mean elevation, 860
Western snow-survey systems, map of, 874

Yakima Basin
  Precipitation-data, 880, 881, 882
  Proposed snow-survey system, 878
  Relation of precipitation and runoff, 883
Yakima, Chelan, and Skagit basins, Cascade Range, map of, 879

INDEX OF NAMES FOR PART III-C

J. E. Church, 1027, 1032, 1044
Elmer Fisher, 1004
D. B. Freeman, 1027
Halbert P. Gillette, 1015
H. T. Gisborne, 1050, 1053
George F. Hopkins, 1006
Norbert Leupold, 1004
James C. Marr, 1021
Fred Merryfield, 999
George W. Mindling, 1046
O. W. Monson, 1033
Clarence Pedersen, 1046
Otto N. Rugen, 1033
J. C. Stevens, 1011
H. U. Sverdrup, 1045
F. M. Veatch, 1014
Vernon Warren, 999
Washington Water Power Company, 1053
George G. West, 1053

INDEX OF SUBJECTS FOR PART III-C

Actual and predicted runoff above Fort Peck for April to July, 1028
Actual runoff and combined precipitation plus water-content of snow above Fort Peck for March to July, 1030
Actual runoff and precipitation above Fort Peck for April to July, 1028; March to July, 1029
Altitude-zones for White River Basin, 1008
Application of Colburn formula, 1038

Boise River Drainage, Idaho, snow-cover and runoff for, 1022

Cascade Mountains, precipitation-characteristics west of, 999
Climatic cycle, series of beds of sandstone and dark shale recording a, 1017
Climatic cycle, series of limestone beds recording a, 1017
Climatological data for southern Idaho, 1939-40, 1026
Colburn formula, application of, 1038
Comparison of annual precipitation-averages and medians, 1049

Discussion of George W. Mindling's paper "Do climatological averages serve adequately as normals?", 1046
Drainage-Basin, Mud Mountain, 1007
Dry years and their cause, prospective, 1015

Electric service, story of, a film, 1053
Estimated melting rates of River de Flag Drainage-Area, Little Colorado Basin, 1043
Evaporation from snow-cover, 1045

Film, story of electric service, 1053
Flood control-works, snow-melt problem as affecting design of, 1033
Forecasting spring runoff above Fort Peck, revised procedure for, 1027
Form for recording spring-flow measurement, 1024
Frequency of monthly precipitation in terms of the average, 1047

Heat consumed in raising temperature of snow, 1042

Hydrological investigation for Mud Mountain Reservoir, 1006
Hydrology of Mud Mountain Reservoir, 1013

Isotherms and zones of equal melting of River de Flag Drainage-Area, Little Colorado Basin, 1039

Lengths and dates of four series of triple-progression cycles, 1021
Limestone beds recording a climatic cycle, 1017

Mass-curves of monthly precipitation, 1008
Mass-rainfall curves, 1009
Measured springs, locations of, 1023
Measurement of foothill-springs to determine soil-moisture and ground-water conditions in Snake Basin, Idaho, 1021
Members and guests attending joint Regional Meeting, Seattle, Washington, 1054
Minutes, Regional Meeting, Seattle, Washington, 1053
Monthly precipitation-averages and medians, 1048
Monthly precipitation-data in terms of the average, 1047
Mud Mountain Dam, general plan of, 1012
Mud Mountain Drainage-Basin, 1007
Mud Mountain Reservoir, hydrological investigation for, 1006
Mud Mountain Reservoir, hydrology of, 1013

Need for an index to dryness of watershed, 1021
Nile flood-levels and New England rainfall, 1018

Precipitation-averages and medians
  Comparison of annual, 1049
  Monthly, 1048
Precipitation-characteristics west of Cascade Mountains, 999
Precipitation-data in terms of the average
  Frequency of monthly, 1047
  Monthly, 1047
Predicted values of runoff above Fort Peck for March to July, 1940, 1031
Prospective dry years and their cause, 1015

Radiation-exchanges, 1040
Radiation from Sun and sky, 1045
Relation between mean daily air-temperature and mean daily snow-surface temperature, 1041
Resolution on use of median instead of average, 1053
  Committee on, 1053
Revised procedure for forecasting the spring runoff above Fort Peck, 1027
River de Flag Drainage-Area, Little Colorado Basin
  Isotherms and zones of equal melting of, 1039
  Estimated melting-rates of, 1043
Runoff above Fort Peck for April to July, actual and predicted, 1028
Runoff and precipitation above Fort Peck for April to July, 1028; March to July, 1029
Runoff-values above Fort Peck for March to July, 1940, predicted, 1031

Sandstone and dark shale beds recording a climatic cycle, 1017
Snake Basin, Idaho, measurement of foothill-springs to determine soil-moisture and ground-water conditions in, 1021
Snow-cover and runoff for Boise River Drainage, Idaho, 1022
Snow-melt problem as affecting design of flood control-works, 1033
Snow-surveys at White River Basin in 1940, 1010
Spring-flow measurement, form for recording, 1024
Spring-flow record, 1939-40, for southern and northern Idaho, 1026
Storage-effects of a snow-cover on rainfall, 1036

Transfer of heat from atmosphere, 1045
Triple-progression cycles, lengths and dates of four series of, 1021

Variation in temperature of isothermal layer with time or distance traveled, 1038

Water-content of snow March 1 and actual runoff above Fort Peck for March to July, 1029
White River Basin, altitude-zones for, 1008
White River Basin, snow-surveys in 1940, 1010